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A STUDY OF WIND SHEAR EFFECTS ON AIRCRAFT OPERATIONS AND SAFETY--ETC(U)
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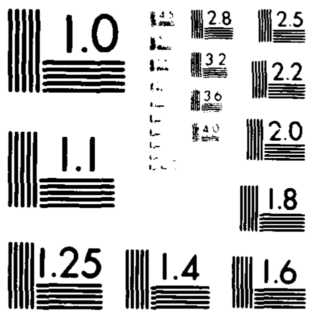

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AR-002-271

AUSTRALIA

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

AD A114763

SYSTEMS REPORT 24

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by

K. W. ANDERSON and B. A. J. CLARK

Approved For Public Release

COPY No

MARCH, 1981

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AR-002-271

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SUMMARY

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Questionnaires completed by 652 military and civilian Australian pilots and air traffic controllers (ATCs) were analysed for subject understanding, detection of wind difficulties, frequency of wind shear and downdraft situations, pilot techniques and forewarning methods.

It seems that the term wind shear *is familiar to many operators but is subject to various interpretations. Specific definitions (like positive wind shear, reverse wind shear, etc.) were often misunderstood. Standard terminology and improved teaching for pilots and ATCs is recommended, along with an extension of theoretical work on optimal piloting techniques in wind shear and other local variations of wind.*

Pilots often found terrain-induced downdrafts, especially at Nowra, Perth and Pearce, and thunderstorm wind shears troublesome. Operations in irregular terrain away from major aerodromes were frequently cited for wind shear hazards. Pilot judgements on the most susceptible aircraft types were not readily explicable in terms of size, landing speed or wing loading.

Pilots and ATCs indicated that currently used cues in wind shear conditions include visual estimates of glideslope departures, precision approach radar observations and aircraft-based measurements of wind or ground speed. Recently developed ground-based remote sensing equipment appears to offer promise for detecting stable wind shears.

A synopsis of wind-involved airliner crashes and a summary of meteorological conditions for the occurrence of local wind variations are included in the report.

POSTAL ADDRESS: Chief Superintendent, Aeronautical Research Laboratories,
Box 4331, P.O., Melbourne, Victoria, 3001, Australia.

Accession For
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Justification
By
Distribution/
Availability Codes
Avail and/or
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DTIC COPY INSPECTED 2

DOCUMENT CONTROL DATA SHEET

Security classification of this page: Unclassified

1. Document Numbers
   (a) AR Number:
   AR-002-271
   (b) Document Series and Number:
   Systems Report 24
   (c) Report Number:
   ARL-Sys-Report-24

2. Security Classification
   (a) Complete document:
   Unclassified
   (b) Title in isolation:
   Unclassified
   (c) Abstract in isolation:
   Unclassified

3. Title: A STUDY OF WIND SHEAR EFFECTS ON AIRCRAFT OPERATIONS AND SAFETY IN AUSTRALIA

4. Personal Author(s):
   K. W. Anderson
   B. A. J. Clark

5. Document Date:
   Date written: February, 1979
   Date published: March, 1981

6. Type of Report and Period Covered:
   Final Report

7. Corporate Author(s):
   Aeronautical Research Laboratories

8. Reference Numbers
   (a) Task:
   AIR 74/14
   (b) Sponsoring Agency:
   AIR FORCE

9. Cost Code:
   73 2251

10. Imprint:
   Aeronautical Research Laboratories, Melbourne

11. Computer Program(s)
   (Title(s) and language(s))

12. Release Limitations (of the document)
   Approved for Public Release.

12-0. Overseas:	N.O.		P.R.	1	A		B		C		D		E	

13. Announcement Limitations (of the information on this page):
   No Limitation

14. Descriptors:
   Wind shear
   Aircraft landing
   Aviation accidents
   Pilot training
   Aviation meteorology
   Flight safety
   Takeoff
   Wind effects

15. Cosati Codes:
   0402
   0102

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It seems that the term wind shear *is familiar to many operators but is subject to various interpretations. Specific definitions (like positive wind shear, reverse wind shear, etc.) were often misunderstood. Standard terminology and improved teaching for pilots and ATCs is recommended, along with an extension of theoretical work on optimal piloting techniques in wind shear and other local variations of wind.*

Pilots often found terrain-induced downdrafts, especially at Nowra, Perth and Pearce, and thunderstorm wind shears troublesome. Operations in irregular terrain away from major aerodromes were frequently cited for wind shear hazards. Pilot judgements on the most susceptible aircraft types were not readily explicable in terms of size, landing speed or wing loading.

Pilots and ATCs indicated that currently used cues in wind shear conditions include visual estimates of glideslope departures, precision approach radar observations and aircraft-based measurements of wind or ground speed. Recently developed ground-based remote sensing equipment appears to offer promise for detecting stable wind shears.

A synopsis of wind-involved airliner crashes and a summary of meteorological conditions for the occurrence of local wind variations are included in the report.

CONTENTS

1. INTRODUCTION

Several aircraft crash reports in recent years have noted the existence of substantial changes in wind vector along the flight path. This wind change phenomenon has become known generically as *wind shear*.

Most of those aircraft crash reports involved airliners on approach to airports outside Australia. Their relevance to Australian aviation conditions was largely unknown and a study of the incidence, severity and localisation of similar phenomena in Australia appeared to be warranted. Investigatory studies were therefore initiated in the Aeronautical Research Laboratories (ARL) and Defence Research Centre, Salisbury (DRCS) of the Defence Science and Technology Organisation, sponsored by the Royal Australian Air Force (RAAF) and supported by the Department of Transport (DOT). The studies were widely based. They embraced:

(a) mathematical modelling of aircraft flight path deviations arising from wind change phenomena (ARL);
(b) sensors and signal processing techniques for remote monitoring of wind conditions, particularly by acoustic sounding (DRCS); and
(c) assessment of the magnitude of any wind shear problems in Australia and of the techniques in current use for dealing with such problems (ARL).

Conclusions from those studies were required to determine the extent to which development of new devices, techniques and/or procedures were necessary or desirable for predicting, measuring and coping with wind shear situations.

Aspects (a) and (b) above are reported separately. This Report covers (c), the ergonomics aspects of the problem, and incorporates information previously published in interim articles and papers (Refs 1, 2, 3, 4, 5).

2. BACKGROUND

2.1 Meteorological Factors

Several meteorological factors can cause wind changes at low level. Within one airmass, low-level wind changes are usually terrain-induced and arise from:

(i) lee effects, where the region in the lee of an obstruction may contain waves, rotors, eddies and/or calms;
(ii) contour effects where the airflow is laminar and parallel to the local surface, resulting in downdrafts and updrafts as the air flows over ridges and gullies; and
(iii) surface roughness effects, where the interaction between the moving airmass and the earth's surface reduces the rate of flow in the lower layers.

These terrain-induced conditions usually exist for appreciable periods of time and are therefore regarded as stable. Other stable wind shear situations can arise from the presence of a low-level jet stream, a marked temperature inversion or a sea breeze established against a moderate pressure-gradient wind.

Transient situations, on the other hand, may change over periods as short as a few seconds. These are usually associated with changing weather, especially frontal movement and storms. The wind around a thunderstorm varies both with time and location. Near the centre there are usually strong updrafts and downdrafts, while in the surrounding air strong shears may be evident. With the passage of frontal conditions, as with thunderstorms, the associated wind will vary both with time and position. Sudden temperature and pressure changes can be expected and hazardous wind conditions can exist in the lower layers of the atmosphere for up to an hour after the passage of the front.

Appendix A elaborates on these factors and on their relevance to Australian aviation and particular localities.

2.2 Aircraft Accidents

Since 1970, accident reports on several airliner crashes have cited wind shear or downdraft as causal or contributory factors. In December 1973 a DC-10 aircraft of Iberian Airlines crashed short of the threshold to RWY 33L at Logan Airport, Boston, Massachusetts. Using data from the retrieved 96-parameter flight data recorder, investigators were able to reconstruct, in detail, the flight path and wind profile. The derived estimates of wind include:

1000 feet*	191 degrees	35 knots
500 feet	200 degrees	24 knots
surface	315 degrees	8 knots.

The investigation of this accident drew attention to the hazards of wind shear. Improved knowledge of those hazards and better investigation techniques have enabled the wind factors in more recent accidents to be identified with confidence.

Appendix B provides a discussion of recent wind-involved accidents and leads to the conclusion that inadequate knowledge of the wind profile on approach constitutes a significant flight safety hazard.

A separate review of DOT records of accidents and incidents involving civilian aircraft during the period 1973 to 1975 did not allow useful trend conclusions to be drawn (due to small sample numbers and insufficient relevant information).

In the period 1958 to 1964, a series of undershoot accidents at the RAN Air Station, Nowra, resulted in three fatalities, four aircraft damaged beyond repair and three other aircraft badly damaged. The general pattern of the accidents was a rapid increase in rate of descent at a late stage of the final approach to RWY 26 with westerly winds. The threshold to RWY 26 was located on the edge of a plateau. In the gully under the approach path the terrain slope was about 1 in 10. The runway itself was somewhat concave with the far end (western end, RWY 08 threshold) being about 15 m higher than the lowest point and about 10 m higher than RWY 26 threshold.

A study of the situation in 1965–66 identified terrain-induced downdraft and misleading visual cues as causal factors in the accidents. Suggestions for remedial action were:

(i) the use of perforated fences, or lines of trees, in the gully to reduce the downwash close to the runway (Ref. 6); and
(ii) the selective painting of the runway surface to improve visual cues (Ref. 7).

Major earthworks were undertaken in the early 1970s with more than 100 000 cubic metres of earth being removed from the raised ground beyond the western end of the runway and placed in the gully at the eastern end. The plateau of the airfield was thereby made effectively longer and flatter with about 200 m of level ground now under the approach path in front of the paved area of RWY 26. This area also serves as an underrun for any aircraft landing short. No major undershoot accidents have occurred at RANAS Nowra since that time. It has been said by some Navy pilots that the point of onset of downdraft now occurs earlier on the approach to RWY 26.

2.3 Terminology

Although the popular understanding of *wind shear* undisputedly involves *wind change*, writers in aviation meteorology appear to be disunited on whether:

(i) wind shear is a scalar or vector quantity;

* In this report, SI units are used exclusively except where current aeronautical usage is in conflict. Accordingly airspeed and wind speed are given in knots, and height and altitude are given in feet. Values are given both in SI units and customary units where appropriate.

(ii) wind shear is a wind difference or a wind gradient;

(iii) a temporal wind variation (as distinct from a spatial wind variation) should be called a wind shear;

(iv) wind variation with height is the only type of spatial wind variation that should be called wind shear; or

(v) variation of the lateral and/or vertical components of wind should be classified as wind shear.

Indeed, some writers seem unaware of the distinctions.

The following typical 'definitions' have been taken from popular aviation journals:

> 'Wind shear is defined as a change in wind direction and/or velocity in a short distance, either vertically or horizontally.' (*Sport Aviation*, Ref. 8); and

> 'Wind shear is normally accepted as being a change in the fore-and-aft, lateral or vertical components of wind.' (*Flight International*, Ref. 9).

Some mention of height is often included, especially in publications on meteorology, e.g.:

> 'The vector difference between the winds at two levels is known as wind shear . . .' (Australian Bureau of Meteorology, Ref. 10).

A paper from the US Weather Bureau (Ref. 11) defines wind shear as the derivative, with respect to height, of the primary air flow (i.e. the ten-minute average wind speed). In a paper by a representative of the US Air Line Pilots Association (Ref. 12), wind shear is regarded as a wind difference related to altitude.

Some modelling studies of aircraft behaviour have used wind variation along the flight path, rather than variation with height, e.g.:

> 'Wind shear is a change of wind speed and/or wind direction over a short distance along the flight path.' (Ref. 13).

From the point of view of the pilot, concerned with the response of the aircraft in flight, the more appealing definitions of wind shear are the less restrictive versions such as provided by the International Civil Aviation Organisation (ICAO):

> 'Wind shear: change in wind direction and/or speed in a relatively short amount of space.' (Ref. 14);

or the American Meteorological Society:

> 'Wind shear—the local variation of the wind vector or any of its components in a given direction.' (Ref. 15).

Nevertheless, none of the above 'definitions' is sufficiently rigorous to satisfy the student of mathematics or fluid dynamics. Further discussion is provided in Appendix C.

The current usage in aviation meteorology is that *vertical wind shear* refers to a change in wind vector (speed and/or direction) with altitude; *horizontal wind shear* refers to a change in wind vector with horizontal displacement. ICAO defines vertical wind shear as:

> '. . . the vector difference obtained by subtracting the wind vector at the bottom of a specified layer of the atmosphere from the wind vector at the top of the same layer.' (Ref. 16).

Melvin (Ref. 17) has noted that the meteorologists' 'vertical wind shear' would be referred to in fluid mechanics terminology as a 'horizontal wind shear'.

Low-level wind shear is defined by DOT (Ref. 18) to include both vertical and horizontal wind shears in the lowest 2000 feet of the atmosphere. Because many writers exclude vertical airflow in their definitions of wind shear, the terms *updraft* and *downdraft* are often used, as appropriate.

A *stable wind shear* is said to occur when the short-term mean winds at the two points of interest are steady, and the resulting wind difference (or gradient) is also steady. Conversely, a *transient wind shear* arises from non-steady wind velocities during changing weather conditions in a particular region.

Turbulence consists of perturbations superimposed on the short-term mean wind, and is therefore regarded as secondary flow. Thus turbulence is not classified as wind shear although the two phenomena often occur together. The cycle period of turbulence would normally not exceed a few seconds. In wind shear the wind is primarily a function of position rather than time; therefore the time rate of change of wind observed from a moving aircraft is related strongly to the aircraft's speed and rate of climb or descent. In this Report, the term *wind structure* is used to encompass the whole state of local airflow.

ICAO has defined (Ref. 16) the qualitative terms light, moderate, strong and severe, for vertical wind shears 0 to 4, 5 to 8, 9 to 12 and more than 12, knots per 30 m (100 feet) of altitude respectively. No particular height interval is specified for the measurement. Although the ICAO definitions deal only with stable vertical shear of horizontal wind, it would be wrong to assume that other types of wind shear (i.e. up/downdraft, transient or horizontal wind shear) are necessarily less important in aviation.

2.4 Aviation Significance

2.4.1 Aerodynamics

Because the lift generated by an aerofoil is a function both of airspeed and angle of attack, changes in the values of these parameters will affect lift and hence the vertical motion of the aircraft. Also an aircraft's inertial (i.e. relative to the ground) velocity is the vector sum of its air velocity and the wind velocity. Hence, because the inertial velocity cannot change instantly, any change in the wind (vertical or horizontal wind) will produce a transient change in the aircraft's air velocity (i.e. airspeed and/or angle of attack) and thereby will affect lift.

With an aircraft trimmed for stable cruise, any wind-induced change of airspeed tends to be negated after a period by a corresponding change of aircraft inertial speed. That speed change would follow from any height change and the drag-thrust imbalance resulting from the original wind change. However, for aircraft at low level and low speed on approach to land, safety margins in height, speed and time are relatively small. If the wind change is rapid enough to exceed the aircraft's acceleration capacity, and is large enough to negate its airspeed margin over the minimum approach speed for the given configuration, then a potential hazard exists.

These effects are described in engineering journals (e.g. Refs 19, 20) and pilot journals (e.g. Refs 21, 22).

2.4.2 Overshoot/Undershoot

In the ICAO code (Ref. 16) on vertical shear of horizontal wind, a *negative shear* is one where the headwind is stronger (or the tailwind is weaker) at the top of an airmass than at the lower levels. This circumstance is referred to as *headwind shear* in the Australian Federation of Air Pilots (AFAP) code (Ref. 23), and unqualified *shear* in the QANTAS code (Ref. 24). In such a wind structure, and with no correcting input by the pilot, a descending aircraft will initially tend to underfly the projected or desired flight path and an ascending aircraft will initially tend to overfly. These effects are illustrated in Figure 1.

The inverse circumstance of headwind weaker (or tailwind stronger) at the top of an airmass than at the lower levels is referred to as *positive shear* (ICAO), *tailwind shear* (AFAP) and *reverse shear* (QANTAS). In this case a descending aircraft will initially tend to overfly and an ascending aircraft to underfly, as illustrated in Figure 2.

DOT (Ref. 18) has defined *overshoot shear* and *undershoot shear* according to the initial effect on an aircraft. Hence the type of shear resulting from a given wind structure depends also on whether the aircraft is ascending or descending. Undershoot shear results from a decreasing headwind; this may be a negative shear for a descending aircraft, or a positive shear for an ascending aircraft. For overshoot shear the reverse holds.

2.4.3 Pilot Response

On encountering a wind shear at low level, the pilot will try to minimise the departure from the desired glideslope and airspeed. A temporary change to the thrust setting will be appro-

priate; however the literature is divided on the question of whether pitch controls should be used to pursue airspeed or rate of descent as the primary control variable (e.g. Refs 13, 25).

Perhaps just as significant as the primary effect of wind shear is the possibility of the pilot overcorrecting, e.g. where an initial overshoot shear on approach leads to an undershoot situation as a result of the pilot reducing thrust for too long. Undershooting (whether as a direct consequence of shear or from overcorrection) has the major accident potential, characterised by a high rate of descent with a small power setting, or a low and slow approach. Conversely, an overshoot situation may be less hazardous as the aircraft should be able to go around, or perhaps land, albeit well past the threshold.

In the situation where a pilot has some forewarning of wind changes likely to be experienced during the approach, he can vary his approach strategy (e.g. flaps, speed, approach path angle) so as to be less affected by the change. Some care may be needed to avoid encroaching on other limits (runway length, maximum flap and tyre speeds, etc.) should the anticipated change not eventuate. Again the literature is not unanimous on approach strategy for wind shear conditions, but some kind of speed additive is usually suggested when a decreasing headwind is expected.

2.5 Wind Sensors

2.5.1 Ground-Based Systems

Tower-mounted anemometers are used for horizontal wind measurements at 10 m above ground level at most Australian Flight Service Units. At Bald Hills in Queensland, towers with instruments at various heights up to 200 m are being used to study three-dimensional transient wind behaviour associated with thunderstorm gusts and fronts (Ref. 26). However, for operational use near aerodromes, high obstructions are unacceptable and therefore some sort of remote sensing technique is necessary for examining wind aloft. At major aerodromes some information is currently obtained from balloon flights, a few times a day at most; data so obtained lack the temporal and spatial resolution for operational use in wind shear detection and measurement, especially in transient conditions.

At DRCS, acoustic sounding techniques have been examined in considerable detail. Acoustic sounding is a ground-based remote sensing technique which exploits the relatively strong interaction between acoustic waves and the small-scale inhomogeneities of air temperature and velocity which are present in turbulent regions of the lower atmosphere. In practice, short pulses of acoustic waves are transmitted upwards into the atmosphere at intervals of typically two to ten seconds using a directional acoustic antenna on the ground. As the pulses travel upwards, various scattering processes (e.g. from small-scale turbulence, inhomogeneities, suspended particles or insects) return a small part of the pulses to the ground. Some of this scattered energy is subsequently collected by one or more acoustic antennae, amplified, and processed to give information on the height and intensity of scattering regions in the lower atmosphere. The maximum operating height range is determined by factors such as the power and frequency of the radiated energy, the size and distribution of scattering inhomogeneities, the atmospheric absorption of the energy of the transmitted pulses, and the ambient noise level which determines the minimum detectable signal level. Typical operating height ranges for low-powered (about 10 to 50 W peak radiated acoustic power) acoustic sounders operating in the frequency range 1 to 3 kHz vary from about 100 m to one kilometre, depending upon the antenna configuration and the ambient noise levels.

When the scattering inhomogeneities are moving relative to a fixed receiving antenna on the ground, the frequency of the scattered acoustic waves observed at the receiver differs from the carrier frequency of the transmitted pulses. The magnitude of these Doppler frequency shifts depends primarily upon the wind velocities at the heights of the scattering regions and the particular antenna configuration employed. For example, a monostatic configuration (co-located transmitting and receiving antennae) can be employed to measure the radial component of the three-dimensional wind field along the path travelled by the transmitted pulses. Alternatively, Doppler wind information can be obtained over a limited height interval using a bistatic configuration (spaced transmitting and receiving antennae). In general, a minimum of three antennae is necessary, using either monostatic or bistatic techniques, to obtain information on the three-dimensional wind field along the path travelled by the transmitted pulses.

A requirement for any remote wind-sensing system for routine operational use at aerodromes is the ability to operate satisfactorily under all conditions likely to be associated with wind shear phenomena, including strong surface winds and turbulence, gusts, etc. The data on relatively simple, low-powered systems with analogue Doppler processing, as employed in the DRCS experimental installation at RAAF Edinburgh, indicate that such systems are not suitable for use as remote sensors at airfields. In general, noise from aircraft on a nearby runway, strong surface winds, heavy rain, etc., has been found to render such systems unserviceable, resulting in possible errors in the computed wind (Ref. 27).

Other studies in acoustic sounding have been conducted at RAAF Point Cook (Ref. 28) and Boulder, Colorado (Refs 29, 30). Another system of ground-based sensors has been used to detect gust fronts by measuring small jumps in temperature or pressure (Ref. 31).

Related techniques under development overseas include radio-frequency sensing (typically frequency-modulated continuous wave at 100 mm wavelength) and laser sensing (continuous or pulsed using carbon dioxide lasers) with Doppler processing. A review of alternative remote sensing techniques has been conducted at DRCS (Ref. 32).

2.5.2 Airborne Systems

It has been claimed that some aircraft-based sensors are useful in detecting wind shear. These include: (i) angle of attack instrumention; (ii) the NASA total energy monitor system (Ref. 33) which displays the rate of change of the combined kinetic and potential energies of the aircraft; and (iii) the 'Safe Flight' device (Ref. 34) which computes the rate of change of horizontal wind and the downdraft drift angle. All of these devices are aids to the recognition of and coping with a wind shear that the aircraft is currently encountering. They are not forewarning devices.

3. QUESTIONAIRE SURVEY

3.1 Objectives

As far as was known no systematic investigation had previously been made either in Australia or overseas about the wind shear experiences of aviation personnel. It was anticipated that a questionnaire survey directed at Australian pilots and air traffic controllers (ATCs) would yield valuable information about the extent of any difficulties with wind shear, and might also provide guidance in the techniques for coping with wind shear if these prove to be necessary or desirable.

A questionnaire was prepared with a view to seeking information from Australian pilots and ATCs on:

(i) their understanding of the wind shear phenomenon and its terminology;

(ii) how they anticipate and recognise wind hazards;

(iii) the frequency, severity and locations of important wind shear situations in Australia;

(iv) their opinions as to the aircraft most affected by, and approach techniques best suited to, wind shear conditions; and

(v) preferences for warning messages relating to the presence of wind shear.

Over one thousand questionnaires were sent out in mid-1976 and about two-thirds of those were completed and returned, an excellent result for voluntary surveys of this type. The response appears to reflect the interest and concern in the topic among the aviation community.

3.2 Subjects

The Australian aviation community includes pilots, ATCs, Flight Service Officers and meteorologists, all of whom might have some useful input into a survey on wind shear.

At the time of the survey, the pilot group[1] was composed of approximately:

1000 military pilots (about one-quarter of whom no longer fly regularly);
2000 regular public transport (RPT) pilots;
1500 other commercial pilots;
15000 private pilots;
5000 glider pilots; and
12000 student pilots.

The ATC group comprised about 270 servicemen and about 1000 DOT employees. Of the latter group, about one-quarter were assigned to tower duties.

Ideally, subjects from each of these groups should have participated in order to obtain the widest experience background. However, for reasons of expedience, the survey was restricted to military pilots, military ATCs, civilian RPT pilots and DOT tower-based controllers. Note that general aviation pilots, Flight Service Officers (who provide an advisory and search-and-rescue watchkeeping service for general aviation aircraft operating outside controlled airspace), aviation meteorologists and meteorological observers could not be included although they doubtless would have made a valuable contribution.

The survey was aimed at operators whose experience was relatively recent, and so an attempt was made to exclude persons who had not being flying or controlling air traffic during the preceding 12 months.

3.2.1 Sample Size

Because the survey sought subjective opinions as well as factual information, it was felt that selected interviews of a small number of operators would be inappropriate. This is why the questionnaire survey of many hundreds of operators was undertaken. Due attention was given to established principles in the formulation of questions (Ref. 35) and the multiple-choice answers.

Table 3.2 gives the numbers of eligible persons (i.e. those having recent experience) in each group, together with the chosen number of persons within each group to whom a questionnaire was dispatched. A full survey of all groups was not practicable because the total cost would have been excessive. A 100% sample size was used for the smaller groups to avoid problems resulting from too small a sample (e.g. bias from an individual's extreme views).

TABLE 3.2

Chosen number of persons in survey in relation to eligible parent populations

	Number of persons in eligible parent population	Chosen number of persons in sample	%
Pilots			
Air Force	613	408	67
Army	95	95	100
Navy	65	65	100
Civilian (RPT)	1960	196	10
Air Traffic Controllers			
Air Force	233	158	67
Army	25	25	100
Navy	12	12	100
Civilian (DOT)	approx. 1000	76	approx. 8

[1] Approximate figures for 1975–76 taken from government records.

3.2.2 Subject Selection

Where the sample size was less than 100%, a technique for subject selection was required to ensure an even distribution of the sample throughout the parent group. It was thought best to stratify the group on the basis of experience: a representative experience cross-section could then be assured. For Air Force pilots, a computer printout of name, age and flying hours was available. The subjects' names were placed in order of flying hours, and every third name rejected. For Air Force ATCs, age seemed to be the best available correlate of experience, so selection was similarly achieved by rejection of every third name in an age listing.

Unfortunately for this survey, similar computer files were not available for civilian pilots and ATCs. For pilots, however, some idea of flying hours (although up to six months out of date) was obtained from DOT records, and the selection was achieved by accepting every tenth name after an ordering procedure based on those hours.

For civilian ATCs, not even a list of names was obtainable so it was not possible to use a technique of controlled or random selection to produce a list of subjects. A technique of haphazard selection was therefore reluctantly used. This was achieved by sending an appropriate number of questionnaires to each ATC tower with instructions that they be issued to the controllers actually performing the aerodrome control duty on that and subsequent shifts. Consequently the civilian ATCs were the only subjects who did not receive a questionnaire and letter addressed to them personally.

A reply-paid envelope was enclosed with each questionnaire, enabling the return of the document to be expedient, independent and direct. This was important as personal and confidential views were being sought.

3.3 Preliminary Surveys

The questionnaire was used in a preliminary survey in order to test the questions for ambiguity, clarity and completeness. This was achieved by issuing questionnaires and subsequently interviewing each of the respondents to discuss his answers. The first version was tested with ten senior Air Force officers, and the revised version was tested with sixteen current Air Force test pilots and four current Air Force ATCs. This procedure proved particularly useful for improving the questionnaire quality and identifying areas of questioning difficulty.

3.4 Split Ballot

It was decided to issue questionnaires to some groups in the form of a split ballot. This is a technique in which the optional answers are presented in reverse order to half of the subject group. This allows an assessment of the ordering bias to be made: a question whose results are independent of the order of the optional answers is referred to as 'tight'; in a 'loose' question, the respondents are influenced by the order of the optional answers.

A split ballot was used for Air Force pilots and ATCs only. This was appropriate because of the large size of those groups and the availability of individuals' data. In the selection technique described in Section 3.2.2, every third man was rejected. Of the two men accepted, the first received version *X* (the direct version) and the second received version *Y* (the reversed version). Consequently, the two versions were distributed to comparable groups of Air Force members. Navy and civilian groups received questionnaires with direct ordering and Army groups received questionnaires with reversed ordering.

3.5 Versions for Pilots

The pilots' questionnaire was produced in several versions, each of about 30 pages, so full duplication of each version here is not practicable. An indication of question wording and answer options can be found in Appendix D where grouped response data are given. The following subject areas were covered:

(i) understanding of the effects of wind shear;

(ii) understanding of the various definitions;

(iii) reading in aviation journals about wind shear;

(iv) cues for anticipation of wind shear;

(v) cues for recognition of effects of wind shear;

(vi) approach strategy in various wind conditions;

(vii) estimation of degree, location and frequency of wind shear conditions;

(viii) susceptibility of different aircraft types to wind shear conditions; and

(ix) opinions of the content and timing of various proposed warning messages.

The differences between the various versions for pilots were relatively small modifications relevant to the experience of the group concerned: e.g. Navy pilots were asked about ship landings, and only military pilots were asked about rotary wing aircraft.

The civilian pilots' questionnaire was distributed after some of the military pilots' questionnaires had been returned. This allowed some further small refinements to be included and these were mostly in the questions about proposed message content.

3.6 Versions for ATCs

Each version of the ATC questionnaire had 13 pages of questions. The following subject areas were covered:

(i) understanding of the effects of wind shear;

(ii) understanding of the various definitions;

(iii) reading in aviation journals about wind shear;

(iv) cues for detection of wind shear;

(v) estimation of degree, location and frequency of wind shear conditions; and

(vi) opinions of the content and timing of information about wind structure.

Only military ATCs were asked questions about ground controlled approaches (GCAs). As for the civilian pilots' version, the civilian ATC version contained a few small improvements, mainly in the questions about wind information. Otherwise the various ATC versions were similar.

3.7 Respondents

3.7.1 Numbers

Table 3.7.1 shows the numbers of questionnaire respondents in relation to the number of questionnaires dispatched, for each functional group.

Some of the addresses were obsolete, such as in cases of recent retirement or posting. As a result several letters were returned unopened to ARL. No doubt some others also failed to reach the addressee, so the precise numbers of questionnaires delivered as intended are not available.

Apart from the foregoing explanations of non-returned questionnaires, it seems that the remaining differences in the return rates from the different functional groups could be just chance variation. This is illustrated by the difference of Air Force ATC return rates, 77% and 63% for versions *X* and *Y* respectively; this is not a significant difference according to a chi-square test at the 0·01 criterion.

TABLE 3.7.1

Number of persons returning questionnaires in relation to chosen sample size

	Number of Questionnaires		
	Dispatched from ARL	Returned to ARL	%
Pilots			
Air Force (Version *X*)	204	141	69
Air Force (Version *Y*)	204	130	64
Army	95	65	68
Navy	65	33	51
Civilian (RPT)	196	93	47
Total	764	462	
Air Traffic Controllers			
Air Force (Version *X*)	78	60	77
Air Force (Version *Y*)	78	49	63
Army	25	17	68
Navy	12	8	67
Civilian (DOT)	76	56	74
Total	269	190	

3.7.2 Representativeness

Efforts to exclude those without recent experience were largely successful. However, a few respondents, mostly Army pilots, indicated that they had not been flying for up to ten years.

In a few of the cases of an obsolete address, the addressee's successor completed and returned the questionnaire. Also, one senior ATC officer withheld the documents from three of his subordinates because he felt they were too inexperienced; three men of his own selection answered the questionnaire.

As a result of the foregoing, and any other sources of interference, some testing of the respondent groups was considered necessary in order to establish whether or not they were adequately representative of the parent populations. Bias could be introduced if, for example, the respondents contained disproportionate numbers from a particular age group, squadron etc. This testing was made difficult by data inadequacies such as incomplete data about civilian ATC age profiles and incomplete personal data supplied by questionnaire respondents.

Nevertheless, where possible, age and rank profiles were compiled for each of the functional groups, and statistical tests (chi-square and Kolmogorov-Smirnov) were used to compare these profiles with those of the parent groups. No significant differences were found at the 0·01 probability level. As an example, Figure 3 gives the age profiles for RAAF pilots for whom suitable data were available. The profiles for both the parent group and the respondent group show a significant peak in the 26 to 34 years age group. Officers above the age of 50 years were not included in the survey.

Table 3.7.2 gives a list of the flying hours which respondents stated that they had logged on the various aircraft types. Imperfections in this list have been caused by (i) truncation and approximations by respondents in answering the question, and (ii) the exclusion of flying experiences of less than 100 hours on any particular aircraft type (e.g. the list does not represent the 60 to 80 hours of basic training flights by many military pilots in the Winjeel aircraft). The table shows an extensive coverage of most aircraft types. As expected, most of the accumulated flying experience was gained on the older types and transport types of aircraft. One feature which became evident only after viewing the table was the low representation from Skyhawk

pilots. It was then discovered that no members of VF805 Squadron had been included in the list supplied by the Navy; presumably the resulting low representation of Skyhawk pilots could introduce some bias into the sampled collective opinion of Navy pilots.

TABLE 3.7.2

Pilot flying hours for aircraft type

Aircraft type	Number of responding pilots with flying hours of: 100 to 499 hours	500 to 999 hours	1000 to 1999 hours	2000 to 3999 hours	4000 hours or more
Andover HS-748	5	9	10	3	
BAC One Eleven	2	0	2		
Bell 47G	1	12	13	9	
Bell 206B	14	15	12		
Boeing 707	0	1	2	4	12
Boeing 727	0	3	8	9	3
Boeing 747	1	0	2	7	
Canberra	2	17	20		
Caribou DHC-4	0	6	16	23	2
Cessna 180	3	1	4	5	
Chinook CH-47	4	3	1		
CT-4A Airtrainer	8				
Dakota C-47	10	10	15	9	
Douglas DC-3	0	0	10	7	16
Douglas DC-4	0	1	1	2	2
Douglas DC-9	1	6	12	11	4
Electra L-188	1	3	9		
F-111C	7	8	3		
Fokker F27	1	7	16	10	12
Hercules C-130	4	3	27	13	
Iroquois UH-1	12	16	46	13	
Macchi MB-326H	128	28	22	2	
Mirage III	11	29	32	3	
Mystère-Falcon 20	2	3	3		
Neptune SP-2H	2	2	8	9	
Nomad N22	2				
Orion P-3	0	4	12	2	
Porter PC-6B	5	6	12	6	
Sabre F-86	20	15	10	1	
Sea King S-61	7	2	1		
Skyhawk A-4G	1	3			
Tracker S-2	0	2	6	3	
Vampire	33	1	5		
Viscount	0	1	3	4	6
Wessex Mk31	6	8	2		
Winjeel	84	25	13	1	

3.7.3 Attitude

Most respondents appeared to react positively to the survey. More than half of those who answered and returned the questionnaire wrote a paragraph or more in the 'general comments' space. Most gave written replies where invited and many expanded on the multi-choice answers as well. The proliferation of written words was not expected and, although welcome, it did add substantially to the analysis time.

Typical of some unsolicited general comments on the principle of the survey are:

'Fine to see such an exhaustive study'

'Should be more of this on other aspects of safety'

'I hope the survey will improve weaker areas of [wind] advice' and

'Are we having enough problems of this type to warrant this investigation?'

There were also a smaller number of negative remarks about the questionnaire quality and approach. Some of the more prominent are:

'Some ambiguity'

'Some multi-choice answers loosely phrased'

'Questionnaire directed at stable shears only'

'Questionnaire generally not applicable to rotary wing experience' and

'A great technical appraisal may tend to switch off the pilot's interest'.

Some respondents were clearly unfamiliar with wind shear problems. For them the survey served as an educational aid by implicit coverage of certain aspects, and as a catalyst for subsequent discussion with their colleagues. Typical remarks include:

'The questionnaire has shown me how little I had thought about wind shear' and

'The questionnaire has highlighted our lack of knowledge'.

3.8 Responses

Tabulation of the responses to the multi-choice questions is given in Appendix D. Because of the unequal numbers of respondents in each group, direct totalling for each of the answer options could be misleading. Therefore these totals have not been included in the tables in Appendix D. Individual questions and corresponding responses are discussed in the following sections.

4. SUBJECT UNDERSTANDING

The questions at the beginning of each questionnaire served to establish the subject as well as to survey the understanding of some relevant terms.

The question: 'What is implied by saying that an aircraft "hit a downdraft"?' resulted in a literal interpretation (i.e. 'the aircraft flew into downwards moving air') by about 80% of ATC respondents and about 60% of pilot respondents. The 'either or both' option (i.e. either the slower headwind or the downwards moving air, or both) was selected by 33% of responding pilots; RAAF pilots were prominent in selecting that option. Table D1 in Appendix D gives complete data.

Table D2 shows that the question: 'What is wind shear?' yielded an emphasis on the 'abrupt change of wind . . .' answer among all groups of respondents. Some emphasised similarity with words like 'gustiness' and 'turbulence'.

The question: 'What is wind gradient?' yielded an emphasis on the 'progressive change in wind speed . . .' answer among all groups. Table D3 contains the response data. Some respondents commented that the 'gradient wind' was the wind interpreted from the pressure gradient or isobars shown on meteorological charts.

The question: 'In which publications have you, in recent months, seen mention of wind shear, or its effects, or accidents related to wind shear?' seemed to be taken as 'Which publications do you read?' by some respondents. The most popular selections were the more general answers (i.e. 'US military publications', 'company newsletters') and 'Aviation Safety Digest'. The percentage of respondents selecting 'none' ranged from 1% for civilian pilots to 41% for Army ATCs. One of the response options, 'Air Accident Digest', was included as a fictitious item in order to give an indication of the reliability of the responses. In this respect it appears to have failed as enquiries prompted by its relatively high response rate indicated that it was confused by the respondents with real publications such as the DOT 'Aviation Safety Digest' and a Navy publication. This was particularly so for civilian pilot respondents as 'Aviation Safety Digest' was unintentionally omitted from the answer options for their questionnaire. Table D4 shows the number of selections for each of the available options.

The question: 'Which of the following terms do you think is correct when the headwind decreases on descent during final approach?' has the following answers which are correct by definition (see Section 2.3):

(1) negative shear (as opposed to positive shear)

(2) headwind shear (as opposed to tailwind shear)

(3) forward shear (as opposed to reverse shear)

(4) undershoot shear (as opposed to overshoot shear).

In the multiple-choice answers, the last of these pairs was offered only in the civil versions of the questionnaire. Table 4.1 gives selected data for the responses. More complete data are given in Appendix D, Table D5.

TABLE 4.1

Response data on wind shear definitions

Answer option	Percentage of respondents who selected 'unfamiliar with these terms'				Ratio of correct to incorrect responses			
	Military pilots	Civilian pilots	Military ATCs	Civilian ATCs	Military pilots	Civilian pilots	Military ATCs	Civilian ATCs
Positive/negative shear	54	20	51	56	1·7	1·5	3·0	1·8
Headwind/tailwind shear	50	24	56	53	7·5	3·6	2·5	2·0
Forward/reverse shear	71	49	67	67	1·2	2·0	1·1	0·9
Overshoot/undershoot shear		32		53		3·6		1·2

For military respondents, the headwind/tailwind option was the most favoured and also the best answered as judged by the correct/incorrect ratios. However, more than half of the military respondents selected 'unfamiliar with these terms' rather than either of those options. Civilian ATCs mostly preferred the positive/negative shear terms, and civilian pilots mostly preferred the overshoot/undershoot shear option. And while fewer civilian pilots selected 'unfamiliar with these terms' the correct/incorrect ratios were lower than for military pilots.

A separate question about vertical/horizontal shear was asked in the civilian versions only. The correct/incorrect ratio was 4·3 for civilian pilots and 1·0 for civilian ATCs (see Table D6). Many of the incorrect responses indicated that there was confusion between the direction of movement of the air and the axis along which wind variation can occur.

Unsolicited comments suggested that the understanding of wind variation problems is related strongly to experience, and that formal training has included little mention of the subject. It was also clear that some respondents had an incorrect appreciation of wind shear effects.

5. DETECTION OF WIND PROBLEMS

5.1 Detection by ATCs

The question: 'What do you actually use to detect wind shear or wind gradient so that you can advise pilots on approach?' allowed multiple selections. 'Reports from aircraft' was selected by nearly 80% of respondents, and 'experience with local conditions' was selected by 48%. Visual factors (cloud, smoke, dust, etc.) and meteorological cues were less frequently noted. Approximately 16% of respondents selected '[there is] usually not enough information to judge'. Most of the military respondents with GCA qualifications selected 'observations of aircraft on Precision Approach Radar (PAR)' as an important cue. Further details of the response data are given in Table D7.

5.2 Anticipation by Pilots

'Experience with local conditions' was the most popular answer by pilot groups to the question: 'What cues do you actually use to anticipate a wind shear or wind gradient on final approach?' Visual cues (such as smoke, cloud, trees, terrain and surface texture) was the next most frequent reply from pilots of helicopter, Hercules, Caribou and Army aircraft. For other pilots, meteorological correlates (such as turbulence and thunderstorms) and advice from others (including ATC, Automatic Terminal Information Service (ATIS) and other aircraft) were selected more frequently than visual cues. Military pilots selected visual drift observations more frequently than observations from aircraft instruments. The reverse was true for civilian pilots. Response data from the various functional groups are given in Table D8 in Appendix D.

5.3 Aircraft Reaction

The question on aircraft response in wind shear (decreasing headwind) or downdraft situations yielded increasing rate of descent, decreasing airspeed, and glideslope departures as the major cues. Table D9 gives more detailed data. Pitch and angle of attack were each selected by less than 20% of respondents. Army pilot respondents noted yaw and wing dropping more than other groups, especially in wind shear as opposed to downdraft.

To distinguish between wind shear (decreasing headwind) and downdraft, several pilots suggested that downdrafts generally caused a quicker response (especially in rate of descent and glideslope departures) than wind shears. Others suggested that it was difficult or unnecessary to distinguish.

Because the combination of a loss of headwind and a downdraft usually produces smaller responses in pitch and angle of attack, it is hypothesised that this combination may be difficult to detect through the degradation of alerting cues. Civilian pilots were asked to nominate the combination most difficult to detect. Although 'loss of headwind and downdraft' was selected more than other combinations, nearly 60% of respondents selected 'difficult to generalise'. (Table D10 contains more details.) This is consistent with the above finding that only a few pilots consciously use pitch or angle of attack as primary cues in the detection and diagnosis of wind-induced difficulties.

Variations in the 'runway picture' (including information from visual approach slope indicators) and the relationship between airspeed and rate of descent (not consequent upon any pilot control inputs) were also cited as subtle cues to wind shear and downdraft. Some pilots of civilian aircraft equipped with Doppler or Inertial Navigation System (INS) equipment use their equipment to measure wind aloft for comparison with surface wind as advised, to detect any change in wind along the flight path as it occurs, and to distinguish between downdraft and wind shear. This technique was mentioned less frequently by military pilots, especially in single place aircraft where, it was claimed, pilot workload would often preclude any regular monitoring. Table D11 gives the response data.

6. FREQUENCY OF WIND SHEAR PROBLEMS

6.1 ATC Opinion

When asked to estimate the frequency of 'dangerous conditions due to wind shear, wind gradient or downdrafts', ATC respondents produced widely differing answers. Furthermore, among the RAAF respondents, the order of the alternative choice answers altered the median selection from annually to three-monthly; however this difference is insufficient to satisfy either the chi-square or the Kolmogorov-Smirnov statistical tests at the 0·01 level. Some respondents commented that the word 'dangerous' was subject to various interpretations. Table D12 gives the results.

Perhaps it is noteworthy that the controllers at Nowra (Navy), Perth (civilian) and Jandakot (civilian) selected the highest median frequencies of monthly to three-monthly. The lowest frequencies of once in three years or longer were selected by Adelaide controllers. Only two or three controllers represented each ATC location; therefore the sample sizes for this analysis were small and the representativeness accordingly uncertain.

6.2 Pilot Opinion

The questionnaire version for pilots included the question: 'Approximately how many times in Australia have you experienced dangerous situations due to wind shear, wind gradient or downdraft?' The pilot respondents also seemed to have difficulty with the word 'dangerous'; several different interpretations were evident. For comparison, the questionnaire sought similar figures for wake turbulence problems. The responses are summarised in Table 6.2.

TABLE 6.2

'Dangerous' situations resulting from unfavourable wind structure: number of responding pilots who indicated the number of incidents in their flying career

Total number of incidents	Number of pilots who have experienced problems resulting from: wind shear or downdraft		wake turbulence	
	Take-off	*Landing*	*Take-off*	*Landing*
Civilian pilots				
No answer	8	9	8	9
Nil	60	29	76	72
1–4	22	36	7	12
5–19	2	12	2	0
20 or more	1	7	0	0
Military pilots				
No answer } Nil }	277	180	269	205
1–4	56	98	67	119
5–19	25	70	29	31
20 or more	11	21	4	14

More than half of the pilot respondents indicated that they had experienced 'dangerous situations' due to wind shear or downdraft on landing. For more than half of those respondents such situations had occurred less than five times in their flying career.

In most respondent groups, the number of individuals who estimated the wind shear problem as greater than the wake turbulence problem exceeded those with the converse opinion by a large ratio. In the case of RAAF pilots, however, this ratio was much smaller (about 4:3 for landing and about 2:3 for take-off). Many of the military respondents who selected wake turbulence as the greater problem made reference to formation flying of jet aircraft.

Civilian pilots were asked to estimate how often wind problems might cause each of them to initiate a go-around on landing. Approximately half of the respondents gave a non-zero answer; this was nearly always less than five times per year, as can be seen in Table D13 in Appendix D.

6.3 Incident Analysis

Following the question described above, the questionnaire versions for pilots asked for a description of the individual's most notable experience with wind shear, wind gradient or downdraft. Again a subsequent question sought comparative data about wake turbulence.

Approximately half of the responding pilots described a condition of some wind difficulty, but many of these were surface problems (such as crosswinds and gustiness) or cruise problems (such as clear air turbulence and mountain waves at higher levels).

Of 143 accounts of low-level wind difficulty, sufficient information was given with 131 to allow the following categorisation:

(i) vertical shear of horizontal wind	31 accounts
(ii) downdraft	47 accounts
(iii) shielding effects	12 accounts
(iv) frontal and thunderstorm	15 accounts
(v) wake turbulence	26 accounts.

These are discussed in further detail below. Pilots' statements have been edited for conciseness.

(i) *Vertical wind shear incidents*

The following are good examples of incidents in this category.

(a) 'Amberley, F-111C, surface wind 270/10 knots, 150 ft wind 300/20 knots ['moderate shear' in the ICAO code]. At 200 feet AGL aircraft rate of descent increased by 500 ft/min to give full red [T-]VASIS indication at 50 ft AGL. One-third afterburner needed to recover.'

(b) 'Avalon, HS-748, surface wind 270/30 knots, 500 feet wind 340/65 knots ['strong shear' in the ICAO code]. At 400 ft AGL, take-off thrust was required to arrest rate of descent.'

The loss of airspeed inducing the pilot to apply maximum thrust, to make a short landing or to go around, is the common feature of this type of incident. Of the 31 incidents in this category, five involved the Boeing 727, four involved the DC-9 and seven involved the Caribou aircraft.

There was insufficient information to allow further categorisation according to meteorological cause (see Appendix A). The incidents were well spread around Australia's airfields, with Brisbane, Nowra, Williamtown, Essendon, Gospers (near Putty, NSW) and Canberra each being mentioned twice.

(ii) *Downdraft incidents*

Examples of this type of incident are:

(a) 'Nowra, Neptune. On a normal approach, the aircraft seemed to "drop out of the sky". A large amount of power (including the use of the jets) was required to recover.'

(b) 'Perth, DC-6. Aircraft failed to climb past 400 ft at V2 speed (with take-off power).'

(c) 'Laverton, Hercules. During short field landing when approach speeds were at "absolute" minimum, the aircraft was "caught out by the sink" on late finals, and landed short.'

The common feature of this type of incident is the usually sudden increase in rate of descent. The pilot generally alters the thrust setting rapidly and possibly initiates a go-around. Several cases of undercarriage damage were reported.

Of the 47 incidents in this category, 13 occurred at Nowra, four at Perth, and four at Laverton. The Porter aircraft type was involved in six of these incidents at various little known locations. The Caribou type was involved in three, and the Boeing 727, Hercules, Tracker, Macchi, Canberra, Neptune and Sea Venom types, two each.

(iii) *Shielding effect incidents*

Typical of incidents in this category are:

(a) 'Puckapunyal, Caribou. Landing in the lee of a hill, the aircraft encountered severe loss of airspeed and increased rate of descent and directional control problems.'

(b) 'Mt Gambier, F27. As the aircraft descended below the level of the pine trees, shielding effects caused an unexpected high sink rate and loss of airspeed.'

(c) 'Aircraft carrier, Wessex. At maximum weight, the aircraft entered the lee of the superstructure and almost struck the water.'

The common feature of this type of incident is high ground, buildings or trees in proximity to the point of take-off or landing. Of 12 incidents in this category, seven involved helicopters, and three involved the Caribou type. They mostly occurred at isolated locations.

(iv) *Frontal and thunderstorm incidents*

Examples are:

(a) 'Sydney, DC-9. Aircraft developed high sink rate (approximately 2500 ft/min) at approximately 400 ft. Airspeed was fluctuating 20 to 30 knots. A line of Cu-Nim was subsequently observed.'

(b) 'East Sale, HS-748. Thunderstorms in area; surface wind 10 to 20 knots; 600 ft wind 35 to 40 knots; 1000 ft wind 60 knots ['moderate' in the ICAO code]. Rough ride on final. Navigator called the wind every 10 seconds.'

Of the 15 incidents in this category, only three were reported by military pilots. Of the civilian aircraft, the Boeing 707 and DC-9 types were each involved three times. Sydney and Brisbane were mentioned four and three times respectively.

(v) *Wake turbulence incidents*

Some of the more notable incidents are:

(a) 'Cessna 180 landing 3 to 4 minutes after Hercules take-off. At 50 to 100 ft AGL, the aircraft rolled out of control to the right. Controls were reversed to complete a full roll before landing.'

(b) 'DC-9 following DC-10 on take-off with 5 nautical miles separation. Aircraft rolled [past] 90 degrees. Used all aileron and was ready to use spoilers.'

(c) 'Sabre in formation stream landing at low threshold speed. Aircraft rolled to left at about 90 degrees per second till wing tip struck runway. Wheels did not touch. Control was regained and the aircraft landed normally.'

Except for formation flying, preconditions for wake turbulence incidents appear to be little or no wind and a heavier preceding aircraft. A variety of aircraft types was involved, and the only types to be mentioned more than once were the DC-9 (three times), Macchi and Porter (twice each).

For the formation flying category of wake turbulence incidents, the only aircraft types to be named more than once were the Vampire (three times) and the Macchi (twice).

7. CRITICAL PARAMETERS

7.1 Worst Aerodrome for Wind Problems

7.1.1 ATC Opinion

When asked to name the Australian aerodrome which, in their opinion, had the greatest wind shear or downdraft problems, about half of the ATC respondents named the aerodrome at which they were currently working. For many civilian and Navy controllers, this was clearly the only place where they had worked for an extended period. Consequently, good correlation is apparent between the number of controllers working at an aerodrome and the number who consider that aerodrome to have the greatest wind shear problems.

Searching for exceptions to that relationship identified Laverton among RAAF controllers, and Perth among civilian controllers; however, of the six respondents naming Perth, three currently work at Perth and two currently work at nearby Jandakot, and it is not known what experience they have had in other parts of Australia.

7.1.2 Pilot Opinion

Pilot respondents were also asked to name the aerodrome which, in their opinion, had the greatest wind shear or downdraft problems. Table 7.1 gives the response data.

TABLE 7.1

Aerodromes nominated as exhibiting the most severe wind shear conditions: responses from 369 military pilots and 93 civilian pilots

Aerodrome	Number of respondents from base	Number of nominations		Runway/s most-named
		as 'worst' aerodrome	as 'second worst'	
Military				
Nowra	28	147 (28)*	18	26
Pearce	22	26 (7)	28	05
Laverton	10	15 (5)	18	23
Point Cook	15	15 (7)	9	22, 26 and 35
Amberley	34	8 (7)	11	33(T)
Canberra	16	8 (3)	8	17(T)
Williamstown	20	5 (1)	6	12(T) and 30(T)
Richmond	39	3 (0)	21	28(T)
Townsville	11	3 (1)	4	01(T)
Civilian	Annual aircraft movements** (thousands)			
Perth	66	16	4	06(T) and 24
Sydney	167	11	12	07, 16(T) and 25
Hobart	16	10	7	12 and 30(T)
Melbourne	106	8	6	34(T)
Canberra	113	3	6	17(T)
Townsville	NA	3	3	01(T)
Wynyard	17	3	2	26(T)
Essendon	67	3	1	17(T) and 35

* Numbers in parentheses indicate the number of local pilots in the total.
(T) indicates runway with T-VASIS.
** Department of Transport records for 1977-78.

For civilian pilots, the most named aerodromes were Perth, Sydney and Hobart. Hobart and Perth are particularly notable because of the relatively low aircraft traffic density (and therefore pilot exposure) for those locations by comparison with Sydney.

For military pilots, Nowra, Pearce and Laverton were clearly identified in that order. Additional factors may have been relevant in some cases; seven of the eight respondents who named Amberley were F-111C pilots and seven of the 15 respondents who named Point Cook were 1FTS instructors currently flying CT-4A Airtrainers.

Navy pilots were divided in their opinion of ship landings compared with aerodrome landings in their susceptibility to wind problems. Most helicopter pilots stated that ship landings were less susceptible, while most respondents with predominantly fixed-wing experience expressed the converse opinion. Table D14 contains the relevant data.

Aerodrome Parameters

Many respondents elaborated on aerodrome features which they believe cause or are associated with wind problems. The main features nominated are:

(i) Where the runway is elevated above the surrounds, causing air to flow downwards after crossing the airfield. Examples included Nowra RWY 26 and ship landings. Gullies under the approach path have caused similar problems at Toowoomba RWY 11 and Laverton RWY 23 according to some respondents.

(ii) Where the aerodrome is in the lee of mountains, and standing atmospheric waves and rotors tend to be encountered on approach. Perth RWY 06 and Pearce RWY 05 were cited as notable examples.

(iii) In rugged terrain where short and one-way strips are used. Many examples in Papua New Guinea were given.

(iv) Where non-uniform airflow occurs over the aerodrome surface and gives conflicting windsock information. Sydney, Point Cook and Cairns were mentioned as examples.

(v) Where approach paths cross water—be it lake, creek, dam, bay or ocean—which are associated with sinking air when daytime convection is established. This phenomenon was cited in connection with Williamtown RWY 30, Point Cook RWY 22, 26 and 35, Richmond RWY 28 and Sydney RWY 34.

(vi) Where noise abatement procedures discourage the use of the runway with the most favourable wind structure. At Sydney, tailwind approaches and landings are not uncommon according to many respondents.

7.2 Worst Aircraft

Pilot respondents were asked their opinions on which aircraft type is most affected by wind shear problems on approach. This seemed to be variously interpreted as:

'Which reacts the most?' or

'In which is recovery most difficult?' or

'In which is detection most difficult?' or

'Which is most critical in the landing configuration?'

Another problem in the comparison of aircraft types is that certain career streams have only original training aircraft in common (e.g. among pilots with experience on the Caribou, very few had experience on Mirage, Porter, F-111C or CT-4A).

7.2.1 Military Pilots

Asked for the aircraft types most affected, approximately one-third of military pilot respondents expressed no opinion, approximately one-third selected their training aircraft, approxi-

mately one-sixth selected the aircraft at their current posting, and the remainder selected an aircraft of a previous posting.

The following list gives the number of times each aircraft was cited:

Winjeel	102 nominations
Caribou	33
Macchi	22
Dakota	21
CT-4A	14
Porter	9
Cessna 180	8
HS-748	7
F-111C	6
Mirage	6
Chipmunk	5
Vampire	4.

However most of the Winjeel nominations were made by current pilots of fighter, maritime and helicopter aircraft. Only four of the 102 Winjeel-nominating pilots had any Caribou experience. Conversely, all of the Caribou-nominating pilots had some experience on Winjeel aircraft. Consequently, the Caribou is deemed to be 'worse' than the Winjeel in this respect. By continuing that process of comparing pairs of aircraft, the following list results:

Caribou (most affected), CT-4A, F-111C, Porter, Dakota, Winjeel, HS-748, Macchi, and Mirage.

It seems that the Macchi and Winjeel are not considered to be so badly affected as the former list would suggest. The reason that the F-111C appears so prominently is that the experience of F-111C pilots mostly includes Winjeel, Macchi, Canberra, and F-111C; from that selection most responding pilots chose F-111C.

Another form of analysis concentrated on the collective opinion of each squadron. The number of respondents from each squadron was compared with the number of them who nominated the squadron aircraft. Only current pilots were included. Table 7.2.1 gives the results: the Dakota, Caribou and CT-4A are identified as 'most affected'. The Winjeel was little nominated in this list because most 1FTS pilots nominated the CT-4A.

Pilots with helicopter experience were asked to nominate the helicopter they considered to be most affected by wind shear or gradient on approach and landing. The following list resulted:

Iroquois (16 nominations), Bell 47G (14), Bell 206B (9), and Wessex (3).

However, it should be noted that ten of the Iroquois nominations were from Chinook or Sea King pilots. Of the 22 current Iroquois pilots, only three nominated it as the most affected.

The same question was analysed by comparison between pairs. Among RAAF pilots, the Iroquois was identified to be worse than the Chinook. Among Army pilots, the Sioux (Bell 47G) and the LOH (Bell 206) were identified as worse than the Iroquois. Among Navy pilots, Iroquois and Wessex were identified as being worse than the Sea King.

The general trend in all cases is that the heavier and more sophisticated helicopters are considered less susceptible than others.

Pilots with experience on both rotary-wing and fixed-wing aircraft were asked to nominate which they considered more susceptible to wind shear. Table D15 gives a summary of the results. The following conclusions were drawn:

(a) Responding pilots who were currently rotary-wing aircraft pilots mostly favoured the 'fixed-wing worse' option.

(b) Responding pilots who were currently pilots of Caribou, Tracker, Dakota, Porter, and CT-4A aircraft mostly favoured the 'fixed-wing worse' option.

(c) Responding pilots who were currently pilots of Hercules, Orion or Mirage aircraft mostly favoured the 'rotary-wing worse' option.

TABLE 7.2.1

Wind shear susceptibility assessment by current pilots for selected military aircraft types

Aircraft Type	Squadron or Unit	Number of nominations as the 'most affected aircraft' by current squadron pilots	Number of squadron respondents who were current on aircraft type	Ratio
A	B	C	D	E = C/D
Dakota	Transport Support Flight, Aircraft Research and Development Unit	9	11	0·82
Caribou	35, 38 Squadrons	16	21	0·76
CT-4A	1 Flying Training School	10	15	0·67
F-111C	1, 6 Squadrons	5	13	0·38
Porter	173 Squadron, School of Army Aviation	5	17	0·29
Macchi	2 Flying Training School	4	22	0·18
HS-748	34 Squadron, School of Air Navigation	1	10	0·10
Mirage	3, 75, 77 Squadrons, 2 Operational Conversion Unit	3	33	0·09
Winjeel	1 Flying Training School	1	15	0·07

7.2.2 Civilian Pilots

From civilian pilot respondents there was a clear trend for jet transports to be most named as the 'most affected' aircraft. Table 7.2.2 gives the number of nominations.

TABLE 7.2.2

Pilot assessment of wind shear susceptibility for selected civilian aircraft

Number of respondents who	Row	Aircraft type: Boeing 727	DC-9	Boeing 707	DC-3	F27	Boeing 747
. . . nominated the aircraft as the 'most affected' type	A	12	10	5	6	5	0
. . . were then current pilots of the aircraft type	B	25	18	9	0	27	8
. . . have flown more than 1000 hours on type	C	20	27	18	33	38	9
Ratio Row A: Row C	D	0·60	0·37	0·27	0·18	0·13	0

Qantas pilots experienced with the Boeing 747, Boeing 707, Electra and DC-3 usually named the Boeing 707.

Domestic airline pilots usually named the Boeing 727 from a flying history including the DC-9 and F27. Those with no Boeing 727 experience usually named the DC-9, while pilots with no jet experience usually named the DC-3 as worse than the Electra or F27.

Civilian pilots were not asked about rotary wing or general aviation aircraft.

7.2.3 Aircraft Parameters

Many respondents elaborated on the features of the aircraft which they believe are associated with the aircraft's susceptibility to wind shear.

For light aircraft, low wing loading and low approach speeds (by comparison with a given wind change) were often cited. For transport aircraft, momentum and power/mass ratios were often stated to be the major parameters. For jets, engine response times and the lack of propeller wash over the wing were stated to be important. The position on the drag curve at which the aircraft operates during approach was said to be a factor for delta and swept-wing aircraft.

STOL aircraft tend to be operated in rugged areas with short runways. Consequently, steep and slow approaches using high lift devices are used. High pilot workload associated with such operations, together with minimal approach speeds, were cited by some respondents as factors.

Helicopter pilots cited operations in which aircraft mass was near the maximum allowable for the actual density altitude. The mode of operation (confined areas and pinnacles) was thought relevant here also. The requirement for a near zero touchdown speed was also mentioned as sometimes important. Some aircraft (fixed and rotary wing) also tend to have a problem in landing due to high pilot workload.

Doppler or inertial navigation equipment in multi-pilot aircraft was cited by many pilots as an important aid in the early detection and subsequent avoidance of problems due to wind shear.

7.3 Degrees of Severity

Pilots were asked to estimate the *minimum* wind shear severity for:

(i) passing advice to pilots; and

(ii) closing the runway.

The answer options ranged from 5 knots to 60 knots difference in headwind between the runway surface and 500 feet above ground level.

For (i), most respondents selected 10, 15 or 20 knots wind difference between the surface and 500 ft. For (ii), most respondents selected 30 to 40 knots wind difference between the surface and 500 ft. But about 15% of responding pilots would not be drawn to answer question (ii) at all because they stated that, on principle, runways should not be closed. Some indicated that they could not imagine a stable wind difference of 50 to 60 knots existing in Australia. Table D16 contains the total response data.

For the various pilot groups, the distribution of answers to part (i) is shown in Figure 4a and 4b. Although these data are for the six discrete points on the horizontal axis, continuous lines have been used to allow easier interpretation. For the vertical axis, the data have been normalised for the sizes of the different respondent groups.

On Figure 4a it can be seen that more than half of the pilot respondents considered that wind advice should be offered when a wind difference of 15 knots or more is in evidence.

On Figure 4b the differences between the various groups can be seen and it is evident that the difference between the two RAAF groups is noticeably large. A chi-square test indicated that the probability of such a difference being the result of chance variation is less than 0·01. As the selection procedure for receipt of *X* or *Y* version of the questionnaire was devised to avoid bias, it appears that the response difference is at least partly a consequence of the ordering of the answer options.

The results showed a trend for smaller shears to be nominated by pilots of aircraft with lower approach speeds, in both categories (i) and (ii) above. One anomaly is that Hercules pilots nominated criteria which were among the lowest in (i) and among the highest in (ii). Perhaps not much notice should be taken of this anomaly because the question and its answer options cannot be regarded as 'tight' (i.e. the responses were dependent upon the ordering), and also because the number of respondents who nominated the Hercules in this answer was relatively small (viz. 14).

7.4 Height Range

Pilots were asked to select a height range where wind structure information would be the most important. Two answers were sought from each respondent: one estimation for light aircraft and the other for heavy aircraft.

Table D17 in Appendix D gives a summary of the replies. Selected data from that table are graphically illustrated in Figure 5. Again the data are for discrete points on the horizontal axis but are connected by continuous lines for easier interpretation. For the vertical axis, the data have been normalised for the sizes of the different respondent groups. Note that only the RAAF pilot group has relevant experience on both heavy and light aircraft.

The distributions for civilian and Navy pilot respondents show a distinct single peak shape. This peak occurred at 800 ft for heavy aircraft as shown in Figure 5 and 400 ft for light aircraft which is not drawn. For Army pilots, the light aircraft estimation peak occurred at 200 ft. For RAAF pilots, a dual peak distribution was evident; one peak being at 400 ft and the other at 1500 ft, for both light and heavy categories.

From comparison of the RAAF pilots' responses to the *X* version of the questionnaire with their responses to the *Y* version (see Table D17) it is evident that the responses were biased towards options nearer the top of the page. This effect was particularly pronounced for the light aircraft category; for this case, a chi-square test indicated that the probability of obtaining the result by chance is less than 0·01. As the total number of military and civilian respondents for the *X* version was 267 and for the reversed order versions (*Y* and *Z*) was 195, a slight bias towards the smaller height ranges might be present in the pooled results.

Hercules pilots provided the lowest answers for the heavy aircraft section, almost half of them selecting 200 ft. Caribou and Mirage pilots selected some of the highest answers in both sections. Pilots of large propeller-driven aircraft (such as Hercules, Orion, Caribou) showed a trend for small differences between their estimations for heavy and light aircraft. A larger differential was evident for pilots of jet aircraft (such as Canberra, Mirage and F-111C).

Military respondents in the 35 to 46 age group differed from other groups in generally selecting lower heights. In a chi-square test, this difference proved to be significant at the 0·05 level.

From informal written comments, it is apparent that some pilots answered the question: 'In what height range would wind information be useful in planning an approach?' Others clearly answered the question: 'For what height range would wind information be useful for hazard recognition?' The latter group gave the lower estimations. The 0 to 400 ft range could be argued as representing a consensus of pilot opinion about the height range for wind shear hazard recognition.

8. APPROACH TECHNIQUES

8.1 Threshold Speed for Gusts

Responding pilots were asked to describe any increments added to their threshold speed to prepare for gusty conditions.

'Add full gust factor' or, as a near equivalent, 'add 10 to 15 knots' was most popular with most pilots of Hercules turbo-prop transport and Boeing jet transport aircraft. 'No change' was noted by Mirage and Skyhawk pilots, helicopter pilots and some pilots of light military aircraft. 'Add half the gust factor' or its approximate form 'add 5 to 10 knots' was most popular with other groups.

F-111C pilots frequently selected a change in flight path as well as a speed increment. A few of the Macchi pilots and a few of the F27 pilots added the full gust factor, rather than half.

8.2 Threshold Speed for Expected Wind Shear

Pilots were asked how they would alter their approach speed if they knew that the wind at 500 ft was different from the surface wind. Most selected 'no change' as can be seen in Table D18. Some noted that they would not know the wind at 500 ft, at least not confidently. Others stated that 'there was plenty of time for correction below 500 ft'. Those who said that they would

alter their approach speed in such conditions included 60% of Boeing pilots, and 40% of pilots of propeller transports (including HS-748, Caribou, Dakota, F27, Neptune, but excluding Hercules).

The various methods of altering the approach mostly involved a further margin added to the approach speed. These include:

(i) add the 'shear' (understood to be the wind difference between the ground and 500 ft);

(ii) add 5 to 10 knots;

(iii) use 500 ft wind instead of surface wind in calculating the approach speed; and

(iv) aim for a minimum ground speed.

Other changes to the usual method of operation included:

(i) use less or no flap;

(ii) fly a flatter approach path;

(iii) fly with a higher power setting (to avoid jet engine response lag);

(iv) fly a decelerating approach allowing airspeed to 'bleed off';

(v) have the navigator, first officer or copilot 'call the wind' every 10 seconds (when suitable instruments are available);

(vi) aim for a long touchdown; and

(vii) be prepared for a go-around.

For STOL aircraft pilots, the occasion when they expect wind changes (irregular terrain, etc.) is often just the situation when they want their approach speeds to be minimal because of the tendency for runways to be short at remote locations. This is in direct conflict with many of the above. Some pilots referred to other limits to approach speed such as runway surface, braking ability, landing gear and flap speed limits, etc.

Several pilots, military and civilian, referred to pressure to accept a duty runway at city aerodromes with a downwind component of up to 10 knots. Because of problems related to excessive ground speed, they were reluctant to add margins to their airspeed in such circumstances.

8.3 Approach Technique for Unexpected Wind Shear

Natural reaction of pilots to the loss of airspeed or increased rate of descent symptoms (described as wind shear or downdraft cues in Section 4) is to advance the thrust controls. With some jet engines, a time delay of several seconds may occur before the desired useful thrust is fully available.

Other control inputs available to the pilot include elevator and flap controls. Some pilots described a positive pitch change to arrest the rate of descent at the expense of airspeed. Others described the reverse. Few pilots indicated any differing techniques for wind shear and downdraft since, it was claimed, they both have the same effect and, to the pilot, the cause was immaterial.

Perhaps the only reliable conclusions are that pilots cope with the various symptoms as they arise and that the underlying strategies used to determine the appropriate control responses are not easily described by pilots.

8.4 GCA Approach

Military ATC respondents with GCA qualifications were asked about altering the approach path of an aircraft in anticipation of a wind shear. The majority gave an affirmative answer as can be seen in Table D19. Deliberately bringing the aircraft in high or to one side or the early correction of expected drift were commonly quoted as strategies.

Some of those giving a negative answer indicated that a shear is never 100% predictable, and that an incorrect prediction called for dangerous corrections late in the approach. However, the majority view was that a modified approach path helped to make precise touchdowns possible when wind changes along the approach path were expected.

8.5 Go-Around

A go-around—even after the wheels have touched the runway—is formally regarded as a legitimate technique to correct for excessive landing speed or a destabilised or incorrectly judged approach. However, it is clear from informal comments that some pilots regard this practice only as a final recourse to avoid an accident. It is speculated that for a variety of social, professional and commercial reasons, this attitude places a subtle pressure on the pilot to keep his speed additives small and to attempt to recover the glideslope even if the potentially dangerous combination of high rate of descent with low thrust is called for.

9. WARNING MESSAGES

9.1 Current Warnings

The basic wind advice transmitted to pilots by ATC is of the form:

'Wind 240/20 knots gusting 30 knots'

referring to surface wind. Upon request, pilots can obtain area forecasts of the wind at various altitudes. These forecasts are based upon balloon flights and other meteorological data and are renewed approximately every 6 hours. For flight navigation and approach planning, these forecasts are probably useful; but for wind hazard avoidance the basic observational data are often too obsolete to be of much assistance.

At Auckland and Bahrain, ATCs record the wind speed at 2000 ft as advised by pilots of suitably equipped aircraft, and relay that advice on the ATIS. This is useful for approach planning and also as a guide to any wind changes which may be expected at lower levels. Several pilots commented on the effectiveness of this service.

A majority of all pilots, especially civilian pilots, claimed to have sent a warning message regarding wind shear to another pilot at some time. Among Army pilots, however, less than 50% gave a positive reply to this question: Table D20 gives the results.

A majority of all ATCs, especially civilian ATCs, claimed to have sent a wind shear warning message to pilots at some time. The Army ATC group was the only group where more than half said they had never sent such a warning. This compares with pilot statements where about one-third of RAAF, three-quarters of Army, one-sixth of civilian and zero Navy pilots said they had never received a wind shear warning message from ATC.

Of the pilots who had received a wind shear warning, Navy pilots were the only group where a majority considered the current practice to be adequate. The major criticism by the non-Navy pilots was that the messages were not given often enough rather than being too brief. Table D21 gives the summed response data.

For examples of typical messages, both pilot and ATC groups cited a statement of existence such as:

'Caution, wind shear', or

'Previous aircraft advises wind shear on approach'.

Occasionally, a qualitative statement of degree or location of the shear was included, e.g.

'Severe wind shear on short final'.

The condition for the use of the warning message seemed to be either:

(i) when a previous aircraft made a report; or

(ii) as a standard procedure when a certain runway was in use, e.g. Laverton RWY 23.

Among unsolicited comments, complaints about the inaccuracy of surface wind advice was the most common. Pilots suggested that this was the result of anemometer location rather than ATCs' vigilance, and was a problem at some airfields only. It was suggested by some that this was a greater problem than the lack of accurate information about wind aloft.

9.2 Future Warnings

Responding pilots were asked a variety of questions on proposals for future warning messages on the assumption that accurate data for wind on the approach path would be available.

9.2.1 Timing

Many pilots suggested that radio transmissions on final approach were already excessive and that detailed information, where appropriate, should be received early in the approach. This was particularly true for instrument approaches and for all approaches in single place aircraft. Consequently, this may increase the time between wind measurement at a certain point and pilot arrival in the vicinity. Another factor in the determination of this period is the time constant for integration in calculating the average wind. ATCs' opinions on this matter were diverse, with a median of approximately two minutes.

9.2.2 Prerequisite for Warning

The pilots' questionnaire asked about the circumstances under which they would want to have a warning or information about the wind structure. Table D22 contains the results.

Few pilots selected absolute answers like: 'always for particular aircraft' and 'always on certain runways'. The majority of pilots selected some meteorological condition as a prerequisite for appropriate advice. The general statement: 'in weather conditions known locally to cause wind shear' was a little more popular than the more precise: 'when the wind variation between surface and circuit height exceeds some set value'.

In addition, several pilots passed comments on the distracting nature of additional information when the pilot is involved in a sequence of landing checks as well as monitoring various instruments and possibly external visual cues. Unless the information is of considerable importance, perhaps the pilot would be better off without it, some suggested. In justifying that opinion, one pilot asserted that an educated guess was almost as good as accurate knowledge of wind because of conservative allowances in the approach speeds of most aircraft. It was also suggested that more information in the appropriate aerodrome information booklets would reduce the need for radio transmissions to only the most hazardous or unexpected occasions.

9.2.3 Type of Flying

The questionnaire asked pilots which aspects of flying (training, conversion, operations etc.) would benefit most from the availability of wind shear advice. The summed responses are given in Table D23.

Most respondents selected the operational type of answers which would encompass their own type of flying. The only exception to this was for Army pilots where the number of pilots selecting the non-operational options outnumbered those selecting the operational options. Army pilots' explanations of their attitude ranged from the desire to continue to be independent (by using visual external cues primarily), to the expectation that suitable equipment would be located only at major airfields, and therefore not often useful to them. There was also some suggestion from all military groups that an air-transportable or aircraft-mounted device for measuring wind structure might be received more enthusiastically than fixed ground-based equipment.

9.2.4 Mode of Presentation

Responding pilots and ATCs were asked for their preferences in the mode of data presentation. Tables D24 and D25 contain the relevant response data.

Pilot Preferences

'By voice from ATC' was the most popular selection by a good margin over 'numerical head-up display' among all groups. Written comments indicated that despite the instruction to 'ignore cost and technical limitations', some respondents considered the question from within the bounds of their present experience.

Head-up displays were considered desirable but too expensive to justify for many aircraft. Pictorial instruments, paper printout etc. were not popular. Limited space and overcrowding of the instrument panel were cited by some pilots as relevant factors. The single place, high workload aircraft were often cited in this context.

ATC Preferences

For a display in the tower cabin or radar room, responding ATCs gave little support to pictorial displays or paper printout. Digital displays were popular with RAAF groups but all other groups preferred dials. Several respondents preferred dials for direction information and digital displays for average wind speed information.

9.2.5 Content of Verbal Messages

Pilot respondents were asked about the wording of possible messages for pilots on approach. The civilian version of the questionnaire contained more questions on this aspect than did the military versions.

The simple statement of wind speed at one or two heights above terrain (as well as surface wind) was reasonably popular with most groups and drew no critical comments. Qualitative messages were not frequently nominated Some pilots commented that what is severe for one aircraft may be mild to another. Aircraft reaction type messages (e.g. expect loss of airspeed, or expect increasing rate of descent) were generally not favoured over winds description type messages, although some pilots said that the former required less mental processing and might be better understood in a critical situation. The use of rate terms (i.e. wind change per 100 ft of altitude) was favoured by very few pilots.

Military Pilots

Military pilots, in selecting their preferences, avoided the phrases 'headwind decreasing', and 'loss of airspeed'. Indeed no indication of the direction of the shear was commonly selected, other than that implied in the wind-at-altitude type message.

Other favoured messages among the military pilots were similar to the ones in current use, i.e. 'expect wind shear', or, for a more detailed and quantitative version, 'expect 20 knot wind shear at 200 ft'. The latter type of message might be supplied in more severe conditions or on request. Tables D26, D28 and D30 contain further details of the military pilots' responses.

Civilian Pilots

In contrast with the military pilots, few respondents selected a message with no clue about the direction of the shear. The wind-at-altitude type message was preferred as ATIS advice. Boeing pilots (especially 747 pilots) were prominent in this preference. Other than the wind-at-altitude type message, 'expect 20 knot increasing headwind below 500 ft' was the most popular type, especially as a message from the tower (as opposed to the ATIS).

To discriminate between shears of opposite types, respondents showed a slight preference for definition terms like 'undershoot shear' rather than the explicit 'decreasing headwind'. Further details of the civilian pilots' responses are given in Tables D27, D28, D29 and D31.

ATC

ATC respondents were asked about the information they would like to have displayed in the tower cabin or the radar room for relaying to pilots. 'Wind speed and direction at two heights as well as surface' was most preferred. Only Navy ATCs showed a desire for more information than that. More details are given in Table D32.

10. DISCUSSION

10.1 Terminology

The technical literature offers a wide range of definitions for wind shear: there is no universal agreement on whether a wind shear is a vector or scalar quantity, a wind difference or a gradient, a change in vertical or horizontal wind, etc. The pilot and ATC questionnaire responses showed a similar lack of uniformity. The term wind shear is often used loosely to include downdraft and turbulence conditions. ('Wind structure' appears to be more satisfactory as a broad term.) Questions on the more specific definitions (like positive wind shear, reverse wind shear, etc.) were answered incorrectly by many respondents. The use of the terms *overshoot shear* and *undershoot shear* seems to be a more satisfactory alternative, although still subject to possible misinterpretation. It is clear that this topic ought to be studied carefully by an international aviation committee (such as ICAO) with the aim of standardisation on the best available terminology.

Apparently the nature and effects of wind shear have not been well covered in formal training in this country (and probably nowhere else either). Local knowledge has been developed where the need exists but has not often been published in the appropriate aerodrome guides or other appropriate aeronautical publications.

10.2 Significant Factors

The analysis of the pilot and ATC questionnaire replies identified several places and meteorological conditions which are commonly associated with reports of wind shear conditions in Australia. For example, terrain-induced downdrafts at Nowra, Perth and Pearce, and thunderstorm situations (e.g. at Sydney) were clear trends.

There were many reports of other wind shear situations which were not so easy to categorise. For example, wind shears at Hobart could possibly be the result of sea breeze or terrain effects or both. Traffic density is perhaps a further complicating factor. Port Hedland, for example, is known to be affected by a low-level jet stream, but this effect was not prominent in the analysis. This is possibly the result of the low density of aircraft traffic in the pre-dawn hours when the low-level jet is at peak strength.

Aircraft among the most mentioned in connection with wind structure difficulties include heavy jet transports (such as the Boeing 727) and STOL-configured fixed-wing piston-engined aircraft (such as the Caribou).

Pilots of helicopters and light transports operating in irregular terrain (such as mountainous areas, forest areas, near city buildings, etc.) are often exposed to local wind problems induced by the terrain. Shielding and pinnacle effects are examples. Although the affected areas may be of limited vertical extent, the wind changes are sufficiently large to be considered by these pilots as the major wind shear problem for them. The difficulties for a pilot in conditions of local wind shear and mechanical turbulence are compounded in a STOL aircraft on a steep approach to a short and perhaps sloping landing strip. And if the aircraft is operating near its maximum allowable mass for the density altitude, the recovery performance will be at a minimum. Visual cues for the landing task can be distorted in rugged areas (as a result of loss of horizon reference, irregular shape or slope of field or strip, etc.) so that glideslope angle estimations are more difficult for the pilot, even in conditions of good atmospheric visibility. Accordingly the early recognition of wind shear symptoms is probably more difficult in remote areas than at most regular aerodromes.

10.3 Coping with Wind Shear

In wind shear conditions, the most useful cues currently available to a pilot are generally rate of descent, airspeed and visual estimations of glidepath angle and rate of change of glidepath angle. The T-VASIS developed in the 1960s by the then Department of Civil Aviation and ARL is especially useful here. As far as is known, there has never been an undershoot accident at any runway in which T-VASIS was installed, operating and in use. Many of the runways named in connection with wind shear problems do not have a T-VASIS (see Table 6.1). Also, in most of the recent wind-involved airliner crashes, the pilot either did not use or was not able to use any VASI system (see Appendix A).

The pilot groups surveyed, as well as the popular and technical literature on the subject, do not have a uniform strategy for the use of pitch controls (i.e. whether to correct rate of descent or airspeed first, or some combination of both) in regaining the glideslope, although there was no disagreement on the need for rapid thrust changes. More subtle aspects of the detecting and correcting techniques seem to be developed by experience and pilots appeared to have difficulty in making technical explanations of how they do cope. However, it does seem that by comparison with civil transport pilots, military pilots (especially helicopter and STOL transport pilots) tend to make more use of external visual cues at the expense of instrument cues.

It also appears that the technical literature on the topic is incomplete. Certainly, for example, there are some excellent studies on specific aircraft types (mostly airliners) about optimal strategies for use of pitch and thrust controls but the totality of existing studies falls far short of completely covering the broad topic of the appropriate ways in which pilots in representative situations should operate all of the controls available, viz. thrust, elevators, flaps, ailerons and rudder, and if available, leading edge devices and spoilers. This topic should include representative types of aircraft in representative types of wind structure, including crosswind components, and should take account of the cases where the pilot knows in advance what the wind structure is, either completely or imperfectly, or does not know at all. The results ought to apply to pilots with a representative range of skills and should be in a form which allows pilots ready access and practical guidance.

For detection of wind problems, ATCs usually have pilot reports, meteorological advice and experience with local weather. Some military aerodromes are fitted with PAR and after observing the flight path of several approaching aircraft, the GCA controller can often mentally model the wind structure in terms of effect upon aircraft. Some GCA controllers claimed to allow for this in their guidance strategy.

Ground-based devices capable of measuring wind at various altitudes or at various points along the approach path could be useful if they supplied information that was not obsolete. Allowing for a measuring and averaging time of about two minutes, plus time for transmission and interpretation, it is clear that these devices may not be suitable for transient shears such as those induced by frontal or storm conditions. For relatively stable shears, like those induced by terrain or inversion conditions, ground-based measuring devices offer promise.

Autonomous aircraft-based instrumentation, if available, has the advantage of being usable in remote areas. Some aircraft (e.g. those with inertial or Doppler navigation systems) already have a direct readout of current wind speed or alternatively ground speed and these generally provide substantial and useful information when encountering wind shear. Other devices referred to in Section 1.6 may also be useful.

A concept, not yet at the development stage, is to use an airborne radio-frequency or laser sensor directed at the scattering media immediately ahead of the aircraft to allow prediction of airspeed up to say 20 seconds ahead of the present position.

Given the present state of aircraft instrumentation, however, in most instances where pilots need to be informed about wind structure, that advice will need to come through ATC or Flight Service. When data are available (e.g. reports from inertial- or Doppler-equipped aircraft, or from other encounters with wind shear) indicating considerable differences in winds at various altitudes, there is good reason for passing that advice to pilots of nearby aircraft. This may be of use in planning the approach strategy, especially for stable shear situations. The questionnaire responses indicate that a simple message advising the wind speed and direction at a height of 400 ft above ground (as well as at the surface) should be accepted, understood and interpreted at least as well as any other verbal message about wind shear.

When forewarned to expect a change of wind speed on approach, pilots could be expected to be better prepared for the encounter and should therefore respond more safely than otherwise. If the change is likely initially to cause an undershoot, the pilot may elect to increase his nominated approach speed. Additional thrust or a lesser flap setting may also be selected. A lower glidepath angle, which may be undesirable for noise abatement, may occur. Should the wind reduction not eventuate, the aircraft would tend to overfly.

11. CONCLUSIONS

Overseas studies of airliner crashes in the last decade have identified wind shear or other substantial changes of the wind vector along the flight path as causal or contributory factors in a number of cases. Earlier studies by ARL had identified terrain-induced downdraft as a causal factor in a number of landing accidents at RANAS Nowra. The development of methods in Australia and elsewhere for remote sensing of atmospheric winds stimulated this study of what Australian military and civilian pilots and ATCs know about wind structure, what experiences they have had with wind structure and how they have coped, and how real-time wind structure measurements might be communicated and used. A questionnaire which was returned by 462 pilots and 190 ATCs provided information on these topics.

The aviation and meteorological literature surveyed contains numerous definitions of wind shear and associated phenomena. There is considerable variation between definitions and some are virtually diametrically opposed. Discussion, and hopefully agreement, on a set of definitions for universal use in aviation appears to be a matter warranting early attention by the appropriate international body. The questionnaire results have demonstrated that confusion is widespread amongst Australian pilots and ATCs as to how wind shear is defined and how wind structure affects aircraft operation. However, while the plethora of definitions has certainly not helped operator understanding, the confusion seems to be largely a result of a lack of formal training in the topic, both in the military and professional civil streams, and action is needed to redress this situation.

Not surprisingly, pilots and ATCs use a variety of sources or cues to indicate the presence of unfavourable wind structure at airfields, ranging from local experience, visual observations of smoke, dust, drift, clouds etc. to advice from other aircraft. More than half of the responding pilots had experienced 'dangerous situations' due to wind shear or downdraft on landing. For the majority of these pilots, there had been less than five such situations during their flying careers. Military pilots tended to regard wake turbulence as a comparable problem in the case of formation flying of jet aircraft. Civilian airline pilots' experience with wake turbulence was less common but the incidents described were serious.

Military pilots and ATCs identified Nowra, Pearce and Laverton as aerodromes where wind shear or downdrafts existed more frequently than elsewhere. Civilian counterparts were identified as Hobart and Perth. However, at least some of the factors which are predisposing to unfavourable wind structure (viz. thunderstorms, weather fronts, sloping or rugged terrain) are widespread and no airfield can be considered immune.

The Caribou and CT-4A were considered to be the military fixed-wing aircraft most susceptible to unfavourable wind structure in approach and landing. Of the military helicopters, susceptibility appears to decrease with size. For large civilian fixed-wing aircraft, swept-wing jet transports such as the Boeing 727 appeared to be regarded as the most susceptible. Many factors such as wing loading, approach speed, momentum, power/mass ratio, engine response time and cockpit workload appear to bear on these judgements.

A majority of pilots considered that a wind difference of 15 knots or more between surface and 500 ft (160 m) on approach was sufficient to warrant transmission of advice to pilots. Pilot opinion indicated that surface to 400 ft (130 m) on the approach path was a suitable height interval for wind comparison for wind shear hazard recognition. Pilots use a wide and somewhat inconsistent variety of methods for determining what approach speed additives to use (if any) in known conditions of turbulence or wind shear. Pilot techniques used for coping with unexpected wind shear also appeared to form an inconsistent variety, only partly because pilots appeared to have difficulty in describing how they did cope. The literature on the topic is also somewhat

inconsistent and incomplete and this is where the problem of optimal techniques ought to be clarified, e.g. given representative wind structure and aircraft characteristics, studies are needed to determine how pilots with representative skills should use all the available controls to best advantage, and the results will need to be communicated to pilots in a form they can apply in practice.

Opinions on the existing situation with wind shear warnings and conditions were diverse. In general, ATCs claimed to transmit more messages than pilots claimed to have received, but pilots considered that messages with the present brevity were needed more often, except on final approach.

Various instruments and techniques are already in service or are under development for the detection of one or more aspects of wind structure, viz. observations of aircraft on ground-based radar, ground-based acoustic sounders and laser or radio-frequency sounders, and airborne equipment such as inertial navigation systems, total energy monitors, and air data computers. As each of these has some disadvantage as a forewarning device and also because of factors such as cost, size and complexity, none appears suitable for universal application either to airfields or aircraft. The questionnaire included a section intended to elucidate preferences for the type and content of displays of wind structure information from future developments in wind sensing equipment but the responses were diffuse, apparently heavily biased by existing experience and obviously affected by inadequate understanding. With some justification, pilots tended to prefer complete onboard equipment over ground or ground-air sensing systems as targets for future development. The desired content of future displays of wind shear data ranged from (if any) the verbal 'expect wind shear' amongst some pilots to digital and/or analogue displays of wind speed and heading at several altitudes amongst some ATCs. Pilots in general seemed unconcerned about the direction of wind shear, illustrating the need for formal training in this area.

In summary, wind structure and its effects on aircraft is a topic which is not well understood by pilots or air traffic controllers in Australia because of a lack of formal training. Even the largest aircraft suffer wind-related crashes. International agreement on wind structure terminology is needed. Theoretical studies of control strategy for landing in varying winds are incomplete, and existing and new results need to be brought to the attention of pilots. Some improvement in the frequency, timing and content of warnings and cautions to pilots about wind structure appears warranted. Various ground-based and airborne aids for detection of one or more aspects of wind structure already exist but no single device at present is, or appears likely to be, suitable for universal application.

ABBREVIATIONS

AFAP	Australian Federation of Air Pilots
AGL	above ground level
AOA	angle of attack
ARL	Aeronautical Research Laboratories
ATC	air traffic control or air traffic controller
ATIS	automatic terminal information service
DOT	Department of Transport (Australia)
DRCS	Defence Research Centre, Salisbury
FLiP	Flight Information Publication
GCA	ground controlled approach
ICAO	International Civil Aviation Organisation
ILS	instrument landing system
INS	inertial navigation system
NASA	National Aeronautics and Space Administration (USA)
NTSB	National Transportation Safety Board (USA)
PAR	precision approach radar
RANAS	Royal Australian Naval Air Station
RPT	regular public transport (i.e. airlines)
RWY	runway
SAA	Standards Association of Australia
STOL	short take-off and landing
T-VASIS	Tee visual approach slope indicator system
VASI	visual approach slope indicator

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APPENDIX A

Meteorological Conditions for Wind Shear in Australia

1. INTRODUCTION

Local variations in the primary airflow, including horizontal and vertical wind, are known as wind shear, or as downdrafts if downwards moving air is involved (Ref. 5). These variations are of particular importance where aircraft fly at low level such as near aerodromes. These wind changes are usually associated with terrain, transient weather conditions, or differential air mass movement. Knowledge of these meteorological factors aids the prediction of wind shear.

2. METEOROLOGICAL FACTORS

2.1 Terrain Roughness

The interaction between a moving air mass and the earth's surface reduces the rate of flow in the lower layers of the atmosphere. The thickness of the layer affected depends upon wind speed, temperature lapse rate and surface roughness. Through that layer, the wind direction, as well as speed, will usually vary with height. The 'gradient height', defined as the height above ground of the top of the layer, varies from about 250 m for smooth surfaces (such as open sea) to about 500 m for rough surfaces (such as large city centres). Vertical motions of the air (e.g. thermal currents caused by insolation) tend to increase the gradient height. For building design purposes, a model of the relationship between height and wind speed is available in a Standards Association of Australia (SAA) code (Ref. 36).

From graphs of the SAA wind profile models, it can be seen that for the lowest 10 m of the atmosphere, the greatest wind changes occur over the smoothest terrain (category 1 in the SAA code). However, above 30 m, the greatest wind changes occur over the roughest terrain (category 4). For conditions of gale[1] strength or less, such wind changes would not exceed 6 knots per 30 m of altitude, which falls within the ICAO definition of 'moderate' wind shear (Ref. 11).

The SAA model for wind profiles near a change of terrain produces some steeper gradients as the profile model passes from one category to another. Consider, for example, a wind passing across open sea (category 1) before an area of trees and small buildings (category 3) and then an airfield with only a few structures (category 2). For a point two kilometres downstream of the cat. 1/cat. 3 terrain change, the wind speed below 110 m would be largely determined by the rougher surface; above this 'fetch' height, a stronger wind showing less variation with height would predominate as pertaining to smoother terrain. This means that in the case of a 60 knot wind aloft, a wind change of nearly 20 knots could be expected between 60 m and 120 m above ground level, which is 'strong' in the ICAO categorisation of wind shear.

2.2 Shielding

As a special case of the previous 'change of terrain' situation, areas of relative calm can occur in the lee of obstacles such as trees, hangars, hills, etc. The SAA code referred to in the previous section allows for modification of the basic model in these circumstances.

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[1] According to the Beaufort scale, a gale force wind has a mean speed of 37 knots at 10 m above ground. According to the SAA formula, this corresponds to a wind of about 60 knots above gradient height.

These areas are normally of small vertical extent so that an affected aircraft would meet the sudden wind reduction very close to the ground, say below 50 m. A wind reduction of 20 knots in this height range would be classified as a 'strong' wind shear in the ICAO code.

2.3 Mountain Lee Waves

When the wind is light and the lapse rate stable, the airflow over a range of hills is a smooth shallow wave. However, when the wind is stronger (say above 15 knots) or the hill has steep slopes, the airflow may form stationary eddies. In suitable conditions for larger hills and mountains, standing waves with stationary rotors can occur in the lee and affect the airflow at altitudes many times higher than the terrain feature concerned, and for up to 50 km or more downstream. In even stronger winds vertical wind components of up to 40 knots can occur in some locations at relatively low level. In some circumstances rotor streaming (i.e. non-stationary rotor activity) can occur. Rotors are generally very turbulent as well.

In moderate easterly winds, the Darling Range provides mountain wave conditions for the flight paths near Pearce and Perth (Ref. 37).

2.4 Contour Following

The direction of the wind at low levels tends to some extent to conform with the contours of the land. For large surface discontinuities, flow separation and turbulence may occur as discussed in the previous section. For lesser obstructions, the flow often tends to be deflected parallel to ridges or gullies. On the lee side of a hill, the wind may then have a downwards component; indeed the streamlines may be steeper than the hill slope below. Even a small downdraft speed can constitute a serious hazard if it suddenly affects an aircraft at low level. Effects like this can be produced by a large gully under the approach path, where the gully slope at the threshold end exceeds about 5 degrees.

Nowra, Portland and Essendon are examples of aerodromes on a plateau where at least one of the approach paths passes over lower terrain. The contour-following of the air results in a downdraft in the very wind conditions when those approaches will be in use.

Other contour winds such as the Föhn wind, the katabatic (night) wind and the anabatic (day) wind are generally not sufficiently strong or extensive in Australia to be of much significance for powered aircraft operations.

2.5 Thunderstorms

The wind speed in and near a thunderstorm varies both with time and position. In the centre there may be strong updrafts and downdrafts, while in the surrounding air large vertical wind shears may be evident. A rapid increase in wind speed is characteristic of the first gust of an approaching storm. Within about 15 km of a thunderstorm, large fluctuations may occur in an aircraft's vertical and horizontal airspeed regardless of flightpath or ground speed.

In Australia, summer thunderstorms are most prevalent in the northern and eastern coastal regions during the afternoon hours. Winter thunderstorms mostly follow cold fronts (see next section) and occur mostly on the west coast.

As the presence of a thunderstorm is usually obvious, aircraft in low traffic areas can usually avoid any wind difficulties by diverting or holding. In dense traffic areas like Sydney, however, there exists greater pressure on some pilots to continue. Accordingly, thunderstorm encounters can be expected to occur more often at places like that.

2.6 Cold Front

With a cold front, as with thunderstorms, the associated wind will vary both with time and position. The passage of the front may be considered as a wedge of cold air which is undercutting warmer air. Some upwards motion of the warm air occurs before it turns to move horizontally away from the frontal line. Sudden temperature and pressure changes can be

expected at the commencement of the passage, and heavy rain is often present. The most extreme wind changes in the leading gust line occur when the front is fast moving, or the temperature gradient is large. Hazardous wind shears can exist in the lower layers during and after the passage of the front.

In Australia, cold fronts are much more frequent than warm fronts. Aerodromes in the southern regions are the most affected and in that region cold fronts generally move from west to east.

2.7 Low-Level Jet Stream

In the winter months over northern and central Australia, a jet stream with wind speeds of up to 50 knots in the region of 300 m to 1 km above ground frequently exists in the early morning hours (Ref. 38). Like the subtropical jet, which operates at altitudes of up to 12 km and speeds of up to 150 knots, the low-level jet results from horizontal thermal gradients. It usually flows from the north-west or west, and is not associated with any surface frontal activity.

Over flat open terrain, the friction layer is relatively thin and a wind profile from 5 knots at 200 m to 25 knots at 500 m is typical at some locations such as Alice Springs, Daly Waters and Port Hedland. This is about 2 knots per 30 m which, although operating over an extended height range, is classified as 'light'. With higher wind speeds, 'moderate' shears can occur at low level. The low-level jet has its peak intensity in the two or three hours before dawn after radiative surface cooling overnight. After sunrise, thermal convection and turbulence progressively degrade the laminar flow until the low-level jet virtually disappears by mid-morning.

2.8 Temperature Inversion

Being essentially a boundary surface between two separate air masses, an inversion is characterised by discontinuities in the vertical profiles of air density and wind velocity as well as temperature. The inversion is effectively a smooth surface providing little resistance to the upper winds and this usually allows the pressure-gradient winds to have a uniform, turbulence-free flow above. The lower winds are often different in speed, direction or turbulence.

Inversions often develop overnight and are most pronounced in the early morning before convective activity is strong enough to penetrate. Over industrial areas, smog below an inversion may reduce insolation and thereby delay convection. Inversions like that usually form at about 600 m above ground level.

In Australia the most marked wind changes due to inversions occur over the central and northern regions in the colder months. At Mt Isa and Broome, for example, inversions as low as 300 m above ground level can occur and may represent something more of a hazard than those which occur in the vicinity of larger cities.

2.9 Sea Breeze

Where a sea breeze has become established against a moderate pressure-gradient wind, the latter may continue to exist at heights above about 150 m. In consequence, substantial wind changes can occur in the lower levels of the atmosphere. This effect is strongest in the tropics on sunny days but can also be significant where high mountains rise from a narrow coastal plain. Peak activity is usually evident in the early and mid afternoon. Numerous Australian aerodromes adjacent to bays, large lakes or the ocean are so affected; Darwin, Hobart and Sydney are good examples. Generally the sea breeze does not penetrate more than about 15 km inland although much greater penetrations are common at some locations in summer.

2.10 Other Causes

For completeness some other meteorological conditions are included here.

Tropical cyclones, and on a much smaller scale, tornadoes, willy-willies and dust devils are phenomena of intense atmospheric activity near which large wind changes can be expected.

Thermal currents are relatively small rising currents of air produced when the atmosphere is heated locally by the earth's surface. For example a strong thermal current above a hot tarmac can produce horizontal inflow from all surrounding directions, and an uneven wind field results. Downwards moving air can conversely be found over areas of water, forest, and cloud-shaded terrain when daytime convection is established.

3. PUBLISHED ADVICE

3.1 Department of Transport

In the Visual Flight Guide (Aerodrome and Ground Aids) (Ref. 39) for civil aerodromes in Australia, the following warnings can be found.

(a) Bedourie, Queensland: 'Severe turbulence possible on approaches.'

(b) Coffs Harbour, N.S.W.: 'Downdraughts and severe turbulence may be expected in strong wind conditions when using runway 10 for landing or runway 28 for take-offs.'

These warnings do not appear in Aerodrome Diagrams (Ref. 40), the replacement document current in 1980.

3.2 Department of Defence

In the Enroute Supplement (Ref. 41) for military and civil aerodromes in Australia, the following cautions can be found.

(a) Ayers Rock, N.T.: 'Wind shears and turbulence may occur both thresholds during S winds.'

(b) Bedourie, Qld.: 'Severe turbulence possible on APP.'

(c) Coffs Harbour, N.S.W.: 'Severe turbulence may be experienced in strong wind conditions off W end of 10/28.'

(d) Darwin, N.T.: '. . . possibility of wind shear/turbulence on short finals for rwys 11, 18 and 36.'

(e) Dunk Island, Queensland: 'Wind sheers [*sic*] landing 14.'

(f) Nowra, NSW: 'Severe downdraughts may be experienced within 1 NM on APP to rwy 26 when Westerly winds above 7 knots.'

No other cautions were located in the Enroute Supplement. In the Instrument Approach Procedures (Ref. 42), the only wind caution was in relation to Nowra.

4. CONCLUSIONS

The meteorological factors associated with low-level wind shear have been described and several Australian aerodromes were cited in examples. Official cautions are published for only a few aerodromes.

The most severe shears below 300 m AGL are expected to be associated with transient phenomena, such as storms and fronts.

Terrain-induced downdrafts (including mountain lee and contour effects) can be hazardous at some locations, for example Nowra and Perth.

Moderate shears can sometimes occur in areas subject to sea breeze, low-level jet streams or inversions.

APPENDIX B

A synopsis of twelve wind-involved airliner crashes

1. INTRODUCTION

Table B1 gives a selection of airliner crashes in the period from 1972 to 1977. This selection was based on the ready availability of the accident reports and the involvement of wind-induced difficulties as an apparent contributory factor. For eleven of the twelve crashes, the accident reports of the US National Transportation Safety Board (NTSB) were consulted; the remaining accident (Flight 752) was described in a report by the Australian Department of Transport (DOT). The accidents are referred to here by the airline's flight number for convenience.

Flights 63 and 426 were take-off crashes; the others occurred during the approach or on landing.

TABLE B1

Twelve wind-involved airliner crashes

Flight No.	*Airline*	*Aircraft*	*Airport*	*Date*	*Fatalities*
63	Continental	Boeing 727	Tucson, Az.	June 1977	0
66	Eastern	Boeing 727	J. F. Kennedy, N.Y.	June 1975	113
121	Allegheny	DC-9	Philadelphia, Pa.	June 1976	0
317	Air East	Beech 99A	Johnstown, Pa.	Jan. 1974	12
426	Continental	Boeing 727	Stapleton, Denver, Co.	Aug. 1975	0
576	Eastern	Boeing 727	Raleigh, N.C.	Nov. 1975	0
625	American	Boeing 727	St Thomas, Virgin Islands	Aug. 1976	37
669	TWA	Boeing 707	J. F. Kennedy, N.Y.	Dec. 1972	0
752	East West	F27	Bathurst, N.S.W.	May 1974	0
806	Pan American	Boeing 707	Pago Pago, Samoa.	Jan. 1974	97
933	Iberian	DC-10	Logan, Boston, Mass.	Dec. 1973	0
977	Atlantic	DHC-6	Cape May, N.J.	Dec. 1976	4

2. CONTRIBUTORY FACTORS

2.1 Wind Difficulties as a Factor

Records from modern flight data recorders were available in most of the crashes listed, so that in most of these cases the wind profile could be reliably estimated. This led to the identification of wind-induced difficulties as an important contributory factor.

Wind shear or downdraft difficulties were cited by the accident investigation authority as major causal factors in Flights 66, 121, 426 and 752. For Flights 63, 317, 576, 933 and 977, wind shear or downdrafts were cited in the official reports in the context of contributory factors.

For Flight 806, the first official report does not mention the presence of wind difficulties, but a subsequent revision cites destabilising wind changes as a factor. For Flight 669, the official report notes the existence of substantial wind differences between 1500 ft and 500 ft AGL.

2.2 Meteorological Factors

For Flights 63, 66, 121 and 426, the wind disturbances were clearly related to nearby thunderstorms. For Flights 576, 752 and 806, intense raincells are known to have been nearby. For Flights 317 and 625, terrain-induced downdrafts are known to have existed in the approach path. For Flight 933, the difference between surface and aloft winds appears to have been associated with (i) a horizontal temperature gradient related to a cold front movement, and (ii) a surface roughness difference between the aerodrome and the adjacent sea. The vertical wind shears encountered by Flights 669 and 977 seem to have been associated with the movement of warm fronts.

In none of the crashes does the wind problem appear to have originated from a low-level jet stream or atmospheric inversion.

2.3 Aircraft Factors

In four of the accidents (Flights 63, 66, 426, 576) the aircraft was a Boeing 727-200 series (i.e. extended body version). In Flight 625, the original Boeing 727-100 type was involved. In none of the crashes did the aircraft have any ground-speed or wind-speed instrumentation, such as that derived from inertial or Doppler systems.

2.4 Visual Factors

Of the landing crashes, all but one (Flight 752) followed instrument approaches. All but one (Flight 625) were accompanied by rain. Visual illusions or limited visibility were a factor in all of the landing crashes except Flights 625 and 752. Six of the crashes (Flights 317, 576, 669, 752, 806 and 977) occurred in hours of darkness, and the others occurred in the afternoon.

Six of the ten runways where the landing crashes occurred had no visual approach slope indicator (VASI) system in operation. Pilots in two other flights, 625 and 806, claimed not to have seen the operational red-white type VASI. For Flight 977, the NTSB concluded that the pilots could not see the non-standard VASI. In the other landing crash (Flight 576) an operational red-white VASI (on the left side of the runway only) was used but was obscured by rain late in the approach.

2.5 Pilot Factors

Specific verbal warnings of wind shear were received by pilots of Flights 66 and 426 only. Nevertheless, threshold speeds of 5 to 15 knots above reference were flown in all approaches except Flights 121, 317, 803 and 977, in which, apparently, speed additives were not used.

The pilots' failure to detect high rates of descent or their lack of altitude awareness was cited in the official findings for Flights 66, 806, 933 and 977. The Flight 669 report criticised the pilots' use of external visual cues during an instrument approach. The pilots' judgement in the take-off or go-around/continue decision was criticised by the official report for Flights 63, 121, 576 and 625, and the pilot's approach technique (of flying below the glideslope) was cited in the official findings for Flight 317.

2.6 Other Factors

Air traffic was dense in the vicinity of the crashes of Flights 66, 121 and 426. A low fuel state was evident only in the Flight 66 crash. A low threshold clearance height was evident only in the Flight 933 crash. Runway length was adequate for Flight 63 only in the event of a sustained

headwind. Runway length exceeded the minimum requirements in all other cases, but the margin for Flight 625 was small. Other factors cited include company procedures, altitude callouts, aircraft loading and lack of wind shear training.

3. DISCUSSION

Several trends appear to emerge from the preceding summary; however, considerable caution is needed in any attempt to formulate avoidance procedures on the basis of those trends, because the sample is small and inhomogeneous. It would not be justifiable to draw generalisations about contributory factors without a comparison between the above trends for accident aircraft, and the same parameters for airline operations generally. Such parameters would include aircraft types in service, number of runways with VASIs, traffic density at different times and places, etc.

For instance, as stated above, none of the crash aircraft had any ground or wind-speed instruments. In the period of the listing, instruments like that were not commonly fitted, except perhaps in aircraft flying on international routes. Therefore, although a good case can be made on *a priori* grounds for the use of those instruments in detecting and coping with wind shear, the accident listing trend supports but does not establish this proposition beyond doubt.

Further, although visual difficulties were often associated with the listed crashes, it is relevant to note that poor visual cues (usually weather-related) are commonly associated with airliner approach accidents in general.

4. CONCLUSIONS

It seems therefore that the only reliable conclusions which can be drawn from the crash analyses are:

(i) that wind-induced difficulties have contributed to the cause of some major airliner accidents; and

(ii) that inadequate knowledge of wind structure and the resulting effects on aircraft operation is a flight safety hazard.

APPENDIX C

Mathematical definitions of wind shear

Wind shear is defined (Ref. 15) as:

'the local variation of the wind vector or any of its components in a given direction'.

The wind velocity vector is defined as:

$$\mathbf{V} = u\mathbf{i} + v\mathbf{j} + w\mathbf{k}\,, \tag{1}$$

and the position vector is defined as:

$$\mathbf{P} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}\,, \tag{2}$$

where **i**, **j** and **k** are the unit orthogonal vectors for earth-reference co-ordinates, and arbitrary origin. From the above, the wind shear can be interpreted in at least two ways, as follows.

(a) A wind shear may be a wind vector

$$\mathbf{S} = \Delta\mathbf{V} = \mathbf{V}_1 - \mathbf{V}_2\,, \tag{3}$$

i.e., the difference between the wind vectors at points with position vectors $\mathbf{P}_1$ and $\mathbf{P}_2$. The wind shear would then be expressed in the units of velocity.

(b) A wind shear is a velocity gradient, i.e., the derivative of the wind velocity vector with respect to scalar displacement in a given direction:

$$\mathbf{S} = \Delta\mathbf{V}/\Delta L \tag{4}$$

where $\Delta\mathbf{V} = \mathbf{V}_1 - \mathbf{V}_2$ as before,

and $\Delta L = |\mathbf{P}_1 - \mathbf{P}_2| = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$.

The wind shear would then have the dimensions of velocity per unit displacement i.e., reciprocal time.

Wind shear can also be treated as a scalar quantity if only one component of the wind vector is being considered.

In the study of fluid dynamics (Ref. 43) *shear* or *shear stress* is the name given to the friction induced in a viscous fluid by a velocity gradient which exists perpendicular to the fluid flow direction. Consequently, a shear might result from non-zero values of du/dy, du/dz, dv/dx, dv/dx, dw/dx or dw/dy. The x and u variables both exist in the **i** direction and consequently du/dx is specifically excluded from that definition of shear. Similarly du/dy and dw/dz are not regarded as shears in fluid dynamics.

However, in aerodynamics and aviation meteorology, the wider definition of wind shear is accepted. Wind shear can therefore encompass a velocity gradient with respect to displacement in any direction.

APPENDIX D

Questionnaire response data

Number of selections for each of
the available answer options

TABLE D1

Response selections for understanding of 'downdraft'

QUESTION

What is implied by saying that an aircraft 'hit a downdraft'?

(Tick one box.)

	Pilot					Air traffic control				
Respondent Group	RAAF		Army	Navy	Civil.	RAAF		Army	Navy	Civil.
Questionnaire Code	APX	APY	APZ	NPX	RPX	ATX	ATY	ATZ	NTX	RTX
Total Respondents	141	130	65	33	93	60	49	17	8	55
Question Number	1	1	1	1	1	1	1	1	1	1
ANSWER OPTIONS										
The aircraft flew into a slower headwind or a faster tailwind	6	8	2	3	6	1	1	2	0	3
The aircraft flew into downwards moving air	83	74	45	23	60	54	38	11	8	43
Either or both of the above	52	44	17	7	28	5	9	4	0	11
Don't know	0	0	0	0	0	0	0	0	0	0
Other (state briefly)	3	4	3	0	1	0	0	0	0	1

TABLE D2

Response selections for understanding of 'wind shear'

QUESTION

What is wind shear?

(Tick one box.)

	Pilot					Air traffic control				
Respondent Group	RAAF		Army	Navy	Civil.	RAAF		Army	Navy	Civil.
Questionnaire Code	APZ	APY	APZ	NPX	RPX	ATX	ATY	ATZ	NTX	RTX
Total Respondents	141	130	65	33	93	60	49	17	8	55
Question Number	4	4	4	4	4	4	4	4	4	5
ANSWER OPTIONS										
A progressive change in wind speed or direction within an air mass	10	5	7	2	7	3	0	0	1	1
An abrupt change in wind speed or direction caused by relative movement of separate air masses	103	98	41	23	59	50	37	16	6	49
Either or both of the above	25	26	14	7	26	6	11	1	1	6
Don't know	0	0	0	0	0	1	0	0	0	0
Other (state briefly)	5	3	4	2	2	1	1	0	0	0

TABLE D3

Response selections for understanding of 'wind gradient'

QUESTION

What is wind gradient?

(Tick one box.)

	Pilot					Air traffic control				
Respondent Group	RAAF		Army	Navy	Civil.	RAAF		Army	Navy	Civil.
Questionnaire Code	APX	APY	APZ	NPX	RPX	ATX	ATY	ATZ	NTX	RTX
Total Respondents	141	130	65	33	93	60	49	17	8	55
Question Number	5	5	5	5	6	5	5	5	5	6
ANSWER OPTIONS										
A progressive change in wind direction with height	7	3	3	4	3	5	2	4	2	4
A progressive change in wind speed with height	84	66	41	18	61	32	23	7	3	29
Either or both of the above	46	55	18	10	27	21	18	6	2	21
Don't know	2	4	2	1	1	1	4	0	1	2
Other (state briefly)	3	1	3	0	2	2	2	0	0	1

TABLE D4

Responses to question on wind shear in publications

QUESTION

In which publications have you, in recent months, seen mention of wind shear, or its effects, or accidents related to wind shear?

(Tick one or more boxes.)

	Pilot					Air traffic control				
Respondent Group	RAAF		Army	Navy	Civil.	RAAF		Army	Navy	Civil.
Questionnaire Code	APX	APY	APZ	NPX	RPX	ATX	ATY	ATZ	NTX	RTX
Total Respondents	141	130	65	33	93	60	49	17	8	55
Question Number	2	2	2	2	2	2	2	2	2	2
ANSWER OPTIONS										
RAAF Spotlight	31	18	9	5	NA	11	1	0	2	NA
RAAF Flight Digest	36	25	7	5	NA	9	7	3	2	NA
Air Accident Digest	11	9	7	5	64	4	4	0	2	15
Air Clues	24	16	3	5	NA	10	8	0	0	NA
Aviation Week and Space Technology	45	42	16	5	5	13	9	4	0	10
Aviation Safety Digest	46	60	33	10	NA	19	15	7	3	34
Flight International	24	22	16	2	7	11	6	1	0	12
US military publications	64	62	34	20	NA	24	21	6	6	NA
Aircraft	6	5	8	0	2	4	1	0	1	3
ICAO publications	NA	NA	NA	NA	4	NA	NA	NA	NA	1
AFAP publications	NA	NA	NA	NA	56	NA	NA	NA	NA	NA
Company newsletters, circulars or bulletins	NA	NA	NA	NA	77	NA	NA	NA	NA	NA
None	21	17	13	5	1	14	13	7	1	9
Other (state briefly)	15	9	5	1	8	7	5	2	0	11

NA = Not available for selection

TABLE D5

Response selections for wind shear definitions

QUESTION

Which of the following terms do you think is correct when the headwind decreases on descent during final approach?

(Tick one box in each group.)

	Pilot					Air traffic control				
Respondent Group	RAAF		Army	Navy	Civil.	RAAF		Army	Navy	Civil.
Questionnaire Code	APX	APY	APZ	NPX	RPX	ATX	ATY	ATZ	NTX	RTX
Total Respondent	141	130	65	33	93	60	49	17	8	55
Question Number	3A	3A	3A	3A	3A	3A	3A	3A	3A	3A
ANSWER OPTIONS										
Positive shear	20	16	12	6	25	5	2	2	1	7
Negative shear	36	33	14	10	37	13	12	3	2	13
Unfamiliar with these terms	73	75	37	16	19	34	33	9	3	31
Headwind shear	57	50	23	6	44	15	12	2	3	16
Tailwind shear	5	6	4	3	12	7	3	1	2	8
Unfamiliar with these terms	63	69	34	20	22	33	31	8	3	29
Forward shear	17	16	7	1	18	7	5	0	0	7
Reverse shear	15	11	6	1	9	3	5	0	3	8
Unfamiliar with these terms	91	96	48	26	46	41	36	10	3	37
Vertical shear	46	45	13	11	NA	15	11	2	1	NA
Horizontal shear	43	48	27	9	NA	11	13	4	1	NA
Unfamiliar with these terms	39	31	23	10	NA	23	21	5	4	NA
Overshoot shear	NA	NA	NA	NA	11	NA	NA	NA	NA	12
Undershoot shear	NA	NA	NA	NA	40	NA	NA	NA	NA	14
Unfamiliar with these terms	NA	NA	NA	NA	30	NA	NA	NA	NA	29

NA Not available for selection

TABLE D6

Response selections for wind shear definitions

QUESTION

Which of the following terms is correct to describe a wind which is 270°/40 knots at 1000 ft, and 240°/10 knots at 100 ft?

(Tick one box.)

	Pilot	ATC
Respondent Group	Civilian	Civilian
Questionnaire Code	RPX	RTX
Total Respondents	93	55
Question Number	4	4
ANSWER OPTIONS		
Horizontal shear	16	24
Vertical shear	68	24
Unfamiliar with these terms	9	7

TABLE D7

Response selections for ATCs wind shear detection

QUESTION

What do you actually use to detect a wind shear or wind gradient so that you can advise pilots on approach?

(Tick one or more boxes.)

	Air traffic control				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	ATX	ATY	ATZ	NTX	RTX
Total Respondents	60	49	17	8	55
Question Numbers	9	9	9	9	10
ANSWER OPTIONS					
On-site meteorological observations (including balloon flights)	20	8	0	3	6
Meteorological information from ground stations elsewhere	2	4	1	0	3
Experience with local weather conditions	27	25	2	8	30
Smoke or dust	20	10	3	1	12
Jet exhausts on take off	2	1	0	2	3
Reports from aircraft	49	35	11	7	50
Observations of aircraft on PAR	36	24	1	6	NA
Movement of low level cloud in relation to known surface wind	18	11	1	4	24
Usually not enough information to judge	6	10	4	0	10
Not current practice	8	7	4	0	5
Other (state briefly)	1	2	2	0	2

NA Not available for selection

TABLE D8

Response selections for pilots' wind shear detection

QUESTION

What cues do you actually use to anticipate a wind shear or wind gradient on final approach?

(Tick one or more boxes.)

	Pilot				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	APX	APY	APZ	NPX	RPX
Total Respondents	141	130	65	33	93
Question Number	6	6	6	6	7
ANSWER OPTIONS					
Smoke or dust	94	80	49	23	43
Windsocks, trees	93	88	50	18	44
Cloud and cloud shadow movements ..	23	30	25	4	14
Experience with local conditions	121	117	59	33	78
Turbulence	99	91	33	19	64
Thunderstorms	57	65	12	11	59
Drift observations (visual)	69	70	40	19	38
Flying instruments	32	30	20	8	46
Navigational instruments	24	12	9	7	34
Other aircraft (via radio)	65	63	29	13	53
Flight information publications	36	42	6	6	5
Pre flight enquiries	36	43	14	10	16
Advice from ATC (tower) or Flight Service	93	90	28	30	58
Advice from ATIS	NA	NA	NA	NA	51
None	0	2	1	0	0
Other (state briefly)	18	10	6	0	11

NA = Not available for selection

TABLE D9

Response selections for aircraft reaction to wind variation

QUESTION

In practice, what aircraft responses on final approach give you the best indication of:

(i) a wind shear of decreased headwind component; and

(ii) a downdraft?

Specify aircraft type to which these assessments refer.

. . . . (type)

(Tick one or more boxes in each column.)

(i) Decreased Headwind (ii) Downdraft

	Pilot					Pilot				
Respondent Group	RAAF		Army	Navy	Civil.	RAAF		Army	Navy	Civil.
Questionnaire Code	APX	APY	APZ	NPX	RPX	APX	APY	APZ	NPX	RPX
Total Respondents	141	130	65	33	93	141	130	65	33	93
Question Number	11A	11A	11A	11A	11A	11B	11B	11B	11B	11B
ANSWER OPTIONS										
Yaw	9	10	12	3	2	3	5	7	2	3
Wing dropping ..	11	5	4	4	4	14	9	1	0	2
Pitch up	4	1	1	1	8	7	6	6	0	11
Pitch down	17	11	11	3	13	5	9	7	2	10
Increased sink rate ..	100	79	43	18	50	129	117	59	30	82
Reduced air speed ..	105	88	38	22	72	40	34	9	8	30
Increased angle of attack	22	17	4	3	NA	24	22	6	2	NA
Decreased angle of attack	5	7	3	1	NA	9	13	3	1	NA
Short period oscillations ..	8	8	4	2	4	8	7	4	2	13
Long period oscillations ..	1	5	4	0	2	1	4	1	0	4
ILS glide slope departures	NA	NA	NA	NA	73	NA	NA	NA	NA	70
T-VASIS glide slope departures ..	NA	NA	NA	NA	69	NA	NA	NA	NA	66
Other (state briefly)	20	12	6	3	7	17	10	5	2	5

NA Not available for selection

TABLE D10

Response selections for worst combinations of wind shear and downdraft

QUESTION

In your experience, which is the worst combination of wind shear and down/up draft?

Consider *ease of recovery*. (Tick one box.)

ANSWER OPTIONS	Of 93 Civilian Pilots
Gain of headwind and downdraft	12
Gain of headwind and updraft	5
Loss of headwind and downdraft	55
Loss of headwind and updraft	1
Difficult to generalize	17

QUESTION

In your experience, which is the worst combination from the point of view of *ease of detection?*

(Tick one box.)

ANSWER OPTIONS	Of 93 Civilian Pilots
Gain of headwind and downdraft	9
Gain of headwind and updraft	5
Loss of headwind and downdraft	15
Loss of headwind and updraft	9
Difficult to generalize	52

TABLE D11

Response selections for the use of ground speed instruments

QUESTION

For aircraft equipped with ground speed as well as air speed instruments, when have you worked out the wind speed on approach to airfields or in the circuit area?

(Tick one or more boxes.)

	Pilot			
Respondent Group	RAAF		Army	Navy
Questionnaire Code	APX	APY	APZ	NPX
Total Respondents	141	130	65	33
Question Number	10	10	10	10
ANSWER OPTIONS				
Never	47	31	6	6
When wind shear is suspected	21	21	0	6
At selected airfields	11	12	0	2
Always	12	5	0	6
Not applicable	42	46	48	10
Other (state briefly)	15	25	5	6

TABLE D12

Response selections on the frequency of dangerous wind shear or downdraft conditions

QUESTION

From your observations of approach and landing in Australia, on how many days have you seen dangerous conditions due to wind shear, wind gradient or downdrafts?

(Tick one box.)

	Air traffic control				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	ATX	ATY	ATZ	NTX	RTX
Total Respondents	60	49	17	8	55
Question Number	8	8	8	8	9
ANSWER OPTIONS					
Never	13	11	4	0	11
Once in 10 years	3	0	0	0	3
Once in 3 years	6	1	0	0	6
Once in one year	13	7	3	0	11
Once in 3 months	4	12	6	3	10
Once a month	5	9	2	3	7
Once a week	6	4	0	1	2
Other (state briefly)	6	3	0	0	4

TABLE D13

Response selections on wind-induced go-around

QUESTION

Approximately how many times per year would you initiate a go-around due to wind changes along the approach path?

(Insert a *number* in the box.)

ANSWER OPTIONS	Of 93 Civilian Pilots
Nil	52
1–4 times per year	37
5 + times per year	0

QUESTION

Perhaps sometimes you have completed a landing and considered (in retrospect) that you would have landed more safely by going-around and recommencing the approach.

Approximately how many times per year would such an incident be caused by unforeseen wind changes along the approach path?

(Insert a *number* in the box.)

ANSWER OPTIONS	Of 93 Civilian Pilots
Nil	45
1–4 times per year	35
5 + times per year	5

TABLE D14

Response selections on carrier operations

QUESTION

Are carrier operations more or less affected by wind shear, wind gradient or downdrafts than airfields?

(Tick one box.)

ANSWER OPTIONS	Of 33 Navy Pilots
More susceptible	13
Not much difference	2
Less susceptible	12
Can't generalize	3
Don't know	3

QUESTION

For carrier operations, do aircraft appear to be more affected or less affected by wind shear, wind gradient or downdrafts than at airfields?

(Tick one box.)

ANSWER OPTIONS	Of 8 Navy ATCs
More affected	3
Not much difference	0
Less affected	3
Can't generalize	1
Don't know	1

TABLE D15

Response selections for fixed-wing/rotary-wing comparison on wind shear susceptibility

QUESTION

Answer this question only if you have adequate experience on both rotary and fixed wing aircraft.

In general, have you found fixed wing or rotary wing aircraft more susceptible to the effects of wind shear or gradient?

(Tick one box in each column.)

	Take Off				*Landing*			
	Pilot				Pilot			
Respondent Group	RAAF		Army	Navy	RAAF		Army	Navy
Questionnaire Code	APX	APY	APZ	NPX	APX	APY	APZ	NPX
Total Respondents	141	130	65	33	141	130	65	33
Question Number	14	14	14	14	14	14	14	14
ANSWER OPTIONS								
Fixed wing worse	8	3	20	6	17	11	28	9
Rotary wing worse	19	17	8	6	14	17	2	4
Not much difference	5	8	2	2	2	3	0	1
Can't generalize	3	5	4	5	2	3	4	5

TABLE D16

Response selections on wind shear severity

QUESTION

How severe should a wind shear or gradient be before:

(i) the pilot is advised, and

(ii) the runway is closed?

Specify aircraft type to which these assessments refer.

.... (type)

(Tick one box in each column.)

	(i) *advice to pilot*					(ii) *runway closed*				
	Pilot					Pilot				
Respondent Group Questionnaire Code	RAAF APX	 APY	Army APZ	Navy NPX	Civil. RPX	RAAF APX	 APY	Army APZ	Navy NPX	Civil. RPX
Total Respondents	141	130	65	33	93	141	130	65	33	93
Question Number	22A	22A	22A	22A	23A	22B	22B	22B	22B	23B
ANSWER OPTIONS										
5 knots headwind difference between surface and 500 ft	4	5	0	0	2	0	0	0	0	0
10 knots headwind difference between surface and 500 ft	49	21	9	12	29	1	0	0	0	0
15 knots headwind difference between surface and 500 ft	28	39	19	11	35	1	3	0	0	3
20 knots headwind difference between surface and 500 ft	33	48	17	6	20	15	3	4	4	4
30 knots headwind difference between surface and 500 ft	7	18	10	1	2	24	27	15	9	21
40 knots headwind difference between surface and 500 ft	1	4	5	2	0	34	40	16	7	25
50 knots headwind difference between surface and 500 ft	1	3	2	0	0	12	18	8	3	9
60 knots headwind difference between surface and 500 ft	0	2	2	0	0	4	16	6	2	4
Other (state briefly)	13	4	5	0	1	26	18	7	4	16

TABLE D17

Response selections on the height range for wind information

QUESTION

For military/commercial flying at Australian airfields, in what height range would wind structure information be most important?

(Tick one box in each column.)

	heavy aircraft					*light aircraft*				
	Pilot					Pilot				
Respondent Group	RAAF		Army	Navy	Civil.	RAAF		Army	Navy	Civil.
Questionnaire Code	APX	APY	APZ	NPX	RPX	APX	APY	APZ	NPX	RPX
Total Respondents	141	130	65	33	93	141	130	65	33	93
Question Number	20A	20A	20A	20A	21A	20B	20B	20B	20B	21B
ANSWER OPTIONS										
0 to 50 ft	2	1	0	0	0	6	5	2	1	3
0 to 100 ft	7	4	0	2	1	22	6	9	0	9
0 to 200 ft	21	15	0	0	8	28	17	15	8	16
0 to 400 ft	46	29	4	5	24	33	34	12	10	16
0 to 800 ft	11	20	4	9	35	13	18	8	4	11
0 to 1500 ft	29	33	4	8	17	19	34	10	5	3
0 to 3000 ft	3	7	1	2	7	1	5	5	2	0
Below decision height	4	5	1	1	4	2	2	2	1	1
Can't generalize	11	14	13	4	0	9	8	1	1	7
Other (state briefly)	2	3	0	0	0	3	4	2	0	0

TABLE D18

Response selections for approach speeds in wind shear

QUESTION

Do you alter your 'rule of thumb' for calculating approach speed when you know that at (say) 500 ft, the wind is a lot different from the surface wind in speed and/or direction? Assume you know these wind speeds reliably.

(Tick one box.)

	Pilot				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	APX	APY	APZ	NPX	RPX
Total Respondents	141	130	65	33	93
Question Number	9	9	9	9	10
ANSWER OPTIONS					
Yes	37	26	17	5	47
No	97	98	37	25	46

TABLE D19

Response selections for GCA approaches

QUESTION

Have you ever deliberately altered a GCA approach path to compensate for a known or expected wind shear?

(Tick one box.)

	Air traffic control			
Respondent Group	RAAF		Army	Navy
Questionnaire Code	ATX	ATY	ATZ	NTX
Total Respondents	60	49	17	8
Question Number	10	10	10	10
ANSWER OPTIONS				
Not applicable	15	20	15	0
No	15	6	3	1
Yes	30	21	0	7

TABLE D20

Response selections for wind warnings

QUESTION

Have you at some time warned another pilot about a wind shear he was about to encounter?

(Tick one box.)

	Pilot				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	APX	APY	APZ	NPX	RPX
Total Respondents	141	130	65	33	93
Question Number	18	18	18	18	19
ANSWER OPTIONS					
Yes	81	73	32	17	62
No	34	42	27	11	18
Can't remember	27	13	4	5	11

TABLE D21

Response selections on pilot opinions about wind warning messages

QUESTION

How do you regard the current practice relating to warnings of adverse wind shear or wind gradient at airfields?

(Tick one or more boxes.)

	Pilot				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	APX	APY	APZ	NPX	RPX
Total Respondents	141	130	65	33	93
Question Number	7	7	7	7	8
ANSWER OPTIONS					
Never received a warning	44	45	48	0	15
Messages not given often enough	40	31	6	3	42
Messages contain too little detail	14	10	0	2	24
Current practice adequate	26	24	2	16	9
Messages given too often	0	0	2	1	1
Messages too long and complex	0	0	1	0	1
Can't generalize	34	27	7	12	19

TABLE D22

Response selections on the criteria for wind advice

QUESTION

If complete wind structure data (i.e. wind speed and direction at various heights along the approach path) were available, when would you, as a pilot on approach, want to know important details?

(Tick one or more boxes.)

	Pilot				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	APX	APY	APZ	NPX	RPX
Total Respondents	141	130	65	33	93
Question Number	19	19	19	19	20
ANSWER OPTIONS					
Never	0	1	1	1	0
Always	22	8	2	2	17
Always on certain runways	27	21	2	8	10
Always for carrier landings	NA	NA	NA	9	NA
Always in particular aircraft	14	6	2	2	4
When ATC thinks it is important ..	27	32	20	9	20
At certain times of day (state briefly) ..	2	3	3	0	4
In certain weather conditions (state briefly)	31	23	6	3	17
When the surface wind exceeds a certain speed	41	47	22	8	13
When wind structure exceeds 'hazard limits' for aircraft type	47	59	27	11	5
In weather conditions known locally to cause wind shear	90	98	44	25	50
When wind variation between surface and circuit height exceeds a set value ..	60	65	35	13	66
Other (state briefly)	12	6	1	0	7

NA Not available for selection

TABLE D23

Response selections on the application of wind structure data

QUESTION

If complete wind structure data (i.e. wind speed and direction at various heights along the approach path) were available, which aspects of flying would particularly benefit?

(Tick one or more boxes.)

	Pilot				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	APX	APY	APZ	NPX	RPX
Total Respondents	141	130	65	33	93
Question Number	21	21	21	21	22
ANSWER OPTIONS					
Basic training	28	34	23	5	11
Advanced training	30	27	20	6	NA
Bomber conversion	8	12	0	0	NA
Transport conversion	11	25	0	3	NA
Fighter conversion	7	12	0	0	NA
Helicopter training	10	19	14	2	NA
Operational flying (fixed wing)	21	34	12	3	NA
Operational flying (rotary wing)	12	17	12	2	NA
Instrument training	NA	NA	NA	NA	22
Conversion training	NA	NA	NA	NA	17
Agricultural aviation	NA	NA	NA	NA	9
Private operations	NA	NA	NA	NA	11
Charter company operations	NA	NA	NA	NA	18
Reg. 203 operations	NA	NA	NA	NA	14
RPT operations	NA	NA	NA	NA	47
Carrier operations	NA	NA	NA	5	NA
All of the above	83	67	16	18	51
None of the above	6	7	6	1	1
Other (state briefly)	6	6	2	3	0

NA Not available for selection

TABLE D24

Response selections on the presentation of wind structure information

QUESTION

What is the best way to present wind structure information to a pilot on approach? Ignore cost or technical limitations.

(Tick one box.)

	Pilot				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	APX	APY	APZ	NPX	RPX
Total Respondents	141	130	65	33	93
Question Number	25	25	25	25	24
ANSWER OPTIONS					
By voice from ATC	84	67	28	17	31
By numerical display on instrument panel	12	9	6	1	18
By numerical head-up display	22	26	12	5	21
By numerical display elsewhere in cockpit	4	2	0	1	4
By wind profile picture on instrument panel	14	16	10	5	16
By wind profile picture elsewhere in cockpit	0	2	2	3	3
By paper printout in cockpit	1	4	1	0	0
No need for this information	4	1	3	1	0
Other (state briefly)	5	4	2	1	2

TABLE D25

Response selections on the presentation of wind structure information

QUESTION

To present wind structure data to you in the tower cab or radar room, what sort of device would you prefer?

(Tick one box.)

	Air traffic control				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	ATX	ATY	ATZ	NTX	RTX
Total Respondents	160	49	17	8	55
Question Number	12A	12A	12A	12A	12A
ANSWER OPTIONS					
Paper printout	10	3	2	0	9
Digital readout	30	20	1	4	14
Dials	14	17	13	2	22
Picture screen	7	6	3	3	8
Other (state briefly)	1	3	0	0	1

TABLE D26

Response selections on wind messages

QUESTION

In addition to surface wind advice, what sort of message about wind structure would you prefer to receive on approach?

(Tick one box in each column.)

	Automatic Terminal Information Service (ATIS Recorded Message)				At your request on local control			
	Pilot				Pilot			
Respondent Group	RAAF		Army	Navy	RAAF		Army	Navy
Questionnaire Code	APX	APY	APZ	NPX	APX	APY	APZ	NPX
Total Respondents	141	130	65	33	141	130	65	33
Question Number	23A	23A	23A	23A	23B	23B	23B	23B
ANSWER OPTIONS								
Expect wind shear	18	6	5	6	7	7	4	2
Expect wind shear on short finals	44	25	16	8	17	24	6	6
Expect wind shear at 200 ft	7	4	1	1	3	5	2	1
Expect 20 knot wind shear at 200 ft	20	19	9	2	25	24	9	2
Headwind decreasing on short finals	2	3	1	0	1	1	1	0
Headwind decreasing below 200 ft	1	1	1	0	2	2	2	1
Headwind decreasing by 20 knots below 200 ft ..	4	4	3	3	8	6	5	0
Headwind surface 20 knots 200 ft 40 knots	2	7	5	0	10	7	3	2
Headwind decreasing by 10 knots per 100 ft on short finals	4	3	1	1	2	7	4	1
Wind shear: expect loss of airspeed below 200 ft ..	6	5	1	3	2	1	3	0
Wind shear: expect 20 knot loss of airspeed below 200 ft	12	5	6	3	10	8	5	2
Wind shear: expect 10 knots per 100 ft on short finals.	8	6	3	0	7	8	1	1
Wind: surface 260°/20 knots 200 ft 270°/40 knots	29	46	19	9	34	32	15	10
No opinion	1	0	2	0	1	1	1	1
Other (state briefly)	5	1	3	0	5	2	2	1

TABLE D27

Response selections on wind information

QUESTION

What information should be contained in a message from:

(i) Automatic Terminal Information Service, and

(ii) the local controller (on your request)?

You may prefer other phrases, but please base your answer upon information content of the examples below.

(Tick one box in each column.)

	Of 93 Civilian Pilots	
ANSWER OPTIONS	ATIS	Tower
Expect wind shear	18	17
Expect increasing headwind on descent	6	3
Expect increasing headwind below 500 ft	6	9
Expect 20 knots wind shear below 500 ft	4	10
Expect 20 knots increasing headwind below 500 ft	16	30
Headwind: surface 20 knots .. .. 500 ft 40 knots 2000 ft 60 knots	11	7
Wind shear: 4 knots per 100 ft on final	3	10
surface 260°/20 knots .. .. 500 ft 280°/40 knots 2000 ft 280°/60 knots	30	9
No message (other than surface wind)	0	3

TABLE D28

Response selections on wind information

QUESTION

For a wind shear or wind gradient more severe (or less severe) than in the previous examples, how would you alter your previous answers?

(Tick one box in each column.)

(i) 'more severe' (ii) 'less severe'

	Pilot					Pilot				
Respondent Group	RAAF		Army	Navy	Civil.	RAAF		Army	Navy	Civil.
Questionnaire Code	APX	APY	APZ	NPX	RPX	APX	APY	APZ	NPX	RPX
Total Respondents	141	130	65	33	93	141	130	65	33	93
Question Number	24	24	24	24	28	24	24	24	24	28
ANSWER OPTIONS										
More information	75	68	33	19	49	0	1	0	1	7
Less information	0	0	0	0	0	41	29	19	7	28
No change	64	60	30	13	42	92	97	42	23	54

TABLE D29

Response selections for wind shear warning messages

QUESTION

Which of the following descriptions of the wind profile do you prefer for general use in aviation?

(Arbitrary examples used.) (Tick one box.)

ANSWER OPTIONS	Of 93 Civilian Pilots
Wind: surface; 260°/20 knots; 500 ft; 270°/45 knots	33
Wind shear: headwind reducing by 25 knots below 500 ft ..	33
Wind shear: 5 knots per 100 ft below 500 ft	6
Moderate wind shear below 500 ft	9
Moderate undershoot shear below 500 ft	12
No preference	2

TABLE D30

Response selections on wind message format

QUESTION

Which of the following message *types* would you prefer?

1. *Description* of the *wind* structure.

   Examples: (a) headwind decreasing below 500 ft;
   (b) wind shear: 10 knots per 100 ft on finals;
   (c) wind: surface 260°/20 knots; 500 ft 200°/40 knots.

2. *Aircraft response* to the wind structure.

   Examples: (a) expect loss of airspeed below 500 ft;
   (b) expect increasing sink rate below 500 ft;
   (c) expect 10° less drift below 500 ft.

3. *Pilot action* to counteract aircraft response.

   Examples: (a) increase airspeed by 10 knots at 500 ft;
   (b) increase threshold speed by 10 knots;
   (c) steer left 10° at 500 ft.

(Tick one box.)

	Pilot			
Respondent Group	RAAF		Army	Navy
Questionnaire Code	APX	APY	APZ	NPX
Total Respondents	141	130	65	33
Question Number	26	26	26	26
ANSWER OPTIONS				
Prefer *wind description* (1)	90	84	45	21
Prefer *aircraft response* (2)	31	28	15	9
Prefer *pilot action* (3)	4	13	3	0
No preference	3	1	1	0

TABLE D31

Response selections for wind shear warning messages

QUESTION

What message type do you prefer?

(Tick one box.)

	Of 93 Civilian Pilots
ANSWER OPTIONS	
Wind description (e.g. expect decreasing headwind or expect moderate undershoot shear)	67
Aircraft response description (e.g. expect loss of airspeed or expect increasing drift angle)	17
No preference	7

QUESTION

What descriptive terms do you prefer for such a message?

(Tick one box.)

	Of 93 Civilian Pilots
ANSWER OPTIONS	
Words (e.g. moderate, severe etc.)	41
Numbers (e.g. 8 knots per 100 ft or 24 knots loss of headwind) ..	51
No preference	1

QUESTION

How should a shear in one direction be distinguished from a shear in the other?

(Tick one box.)

	Of 93 Civilian Pilots
ANSWER OPTIONS	
By words like undershoot shear, positive shear etc. (see Question 3)	47
By words like increasing airspeed, decreasing headwind etc. ..	35
No preference	2
No distinction necessary	10

TABLE D32

Response selections for wind shear data presentation to ATC

QUESTION

What sort of information would you like to have displayed on such a device?

(Tick one box.)

	Air traffic control				
Respondent Group	RAAF		Army	Navy	Civilian
Questionnaire Code	ATX	ATY	ATZ	NTX	RTX
Total Respondents	60	49	17	8	55
Question Number	12B	12B	12B	12B	12B
ANSWER OPTIONS					
Height of greatest wind shear	2	1	1	0	3
Maximum wind variation below 1000 ft ..	10	9	2	1	19
Height and size of wind shear	15	12	5	0	11
Wind speed and direction at two heights as well as surface	26	21	7	3	23
Wind speed and direction at ten heights as well as surface	6	4	2	4	4
Other (state briefly)	2	4	0	0	1

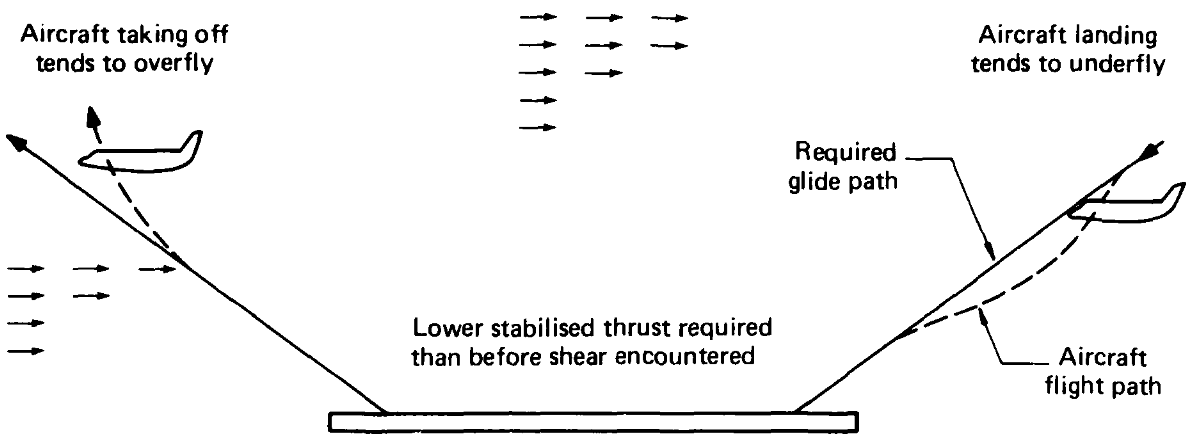

FIG. 1. HEADWIND COMPONENT INCREASING WITH ALTITUDE.

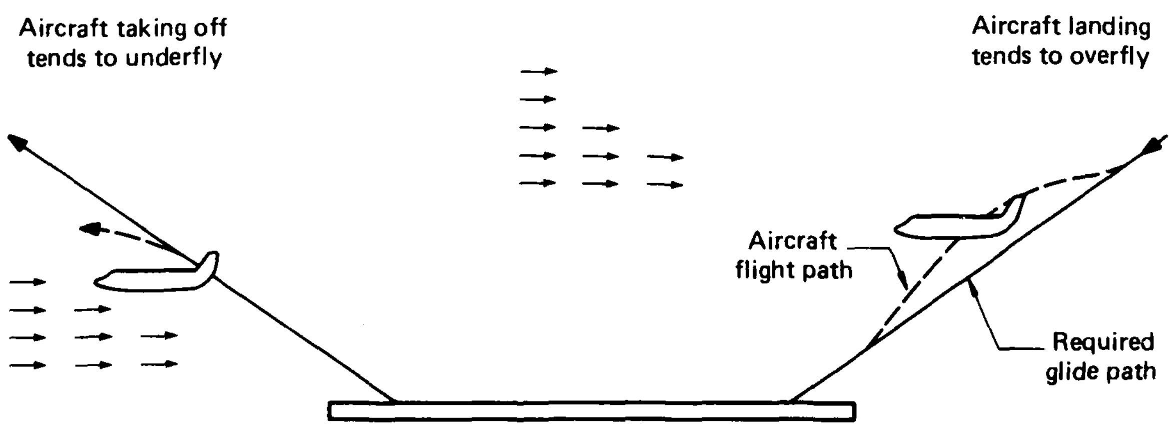

FIG. 2. HEADWIND COMPONENT DECREASING WITH ALTITUDE.

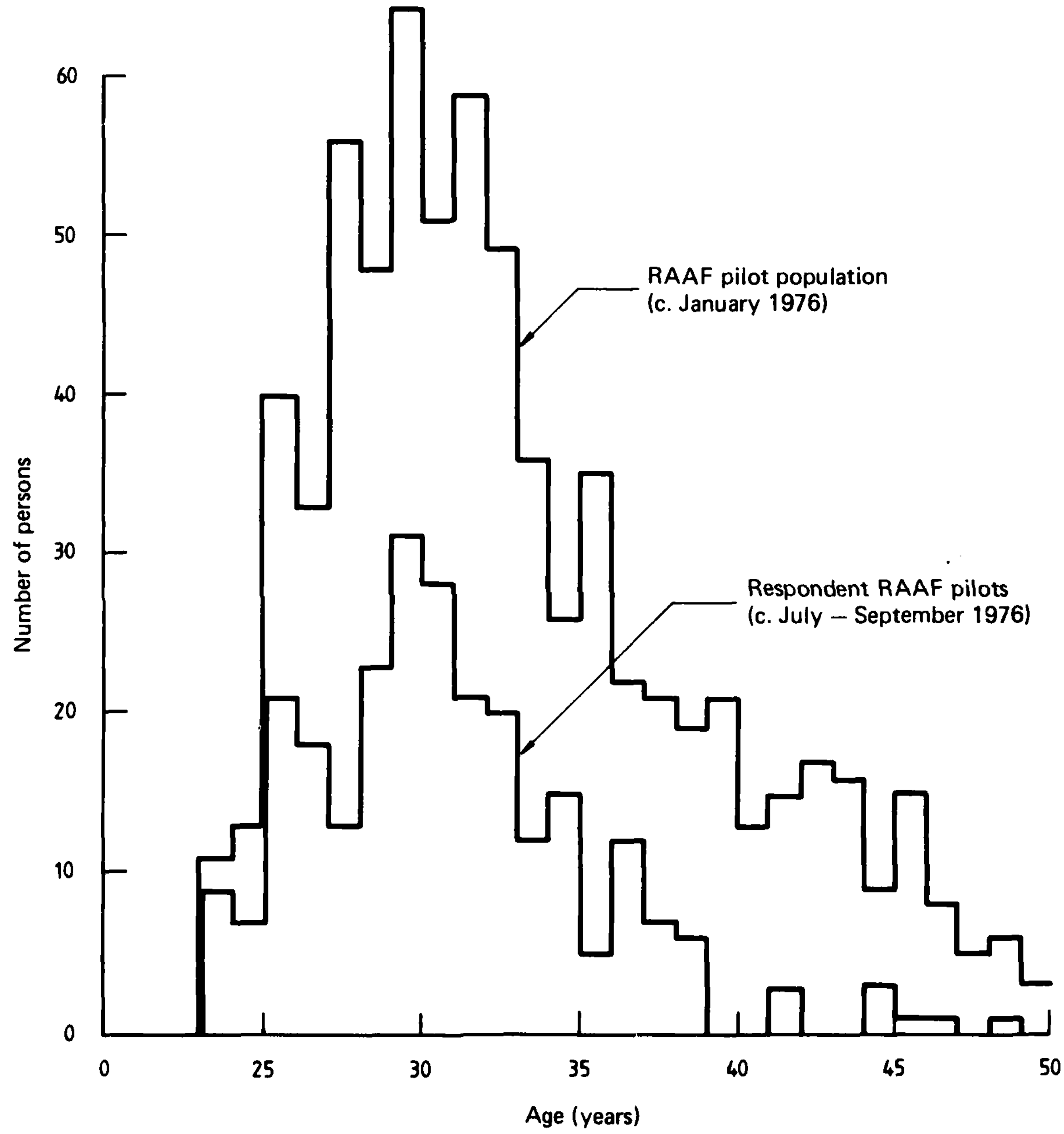

FIG. 3. AGE PROFILE OF RAAF PILOTS : POPULATION AND RESPONDENTS.

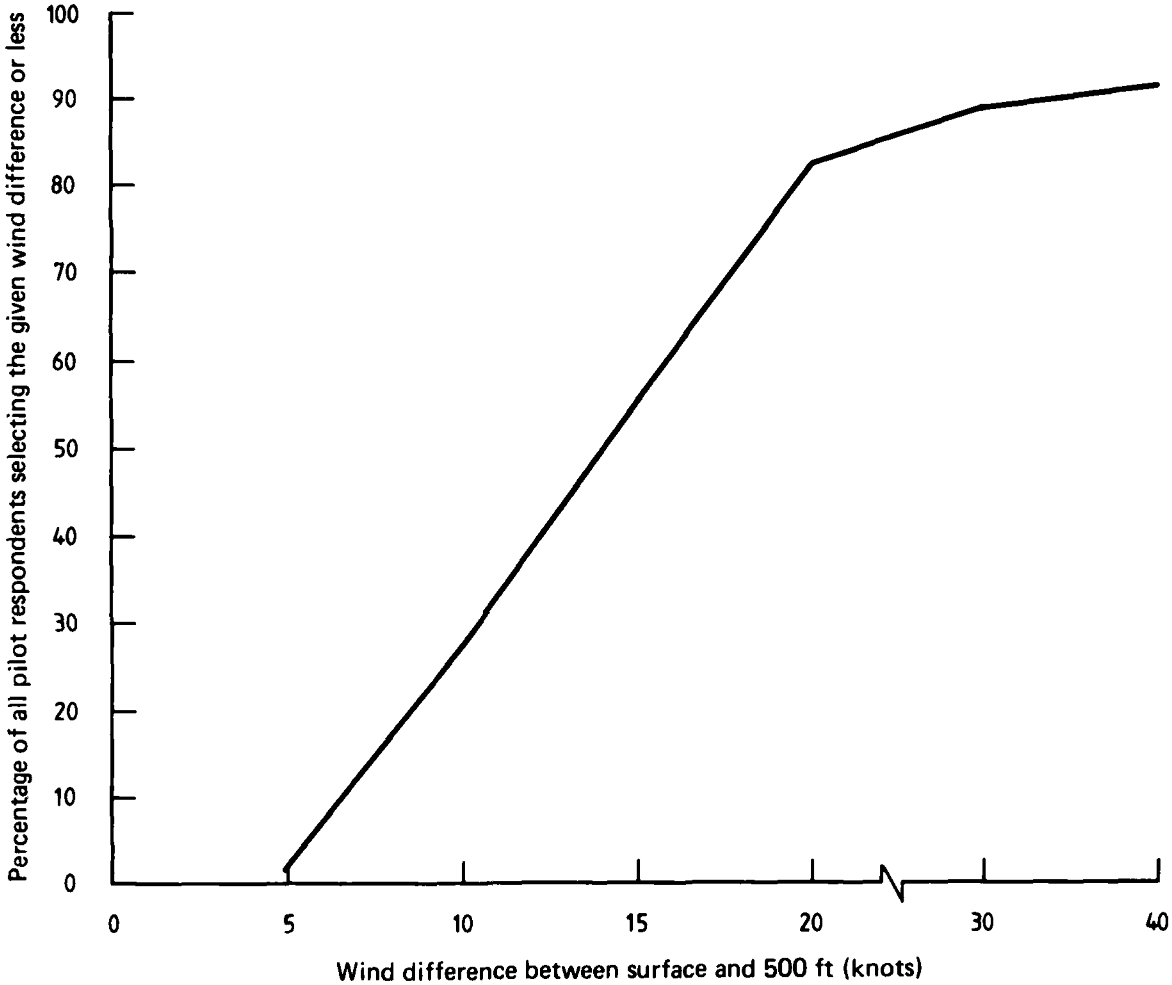

FIG. 4(a) SEVERITY CRITERIA FOR WIND ADVICE: CUMULATIVE PERCENTAGE DISTRIBUTION FOR ALL PILOT RESPONDENTS.

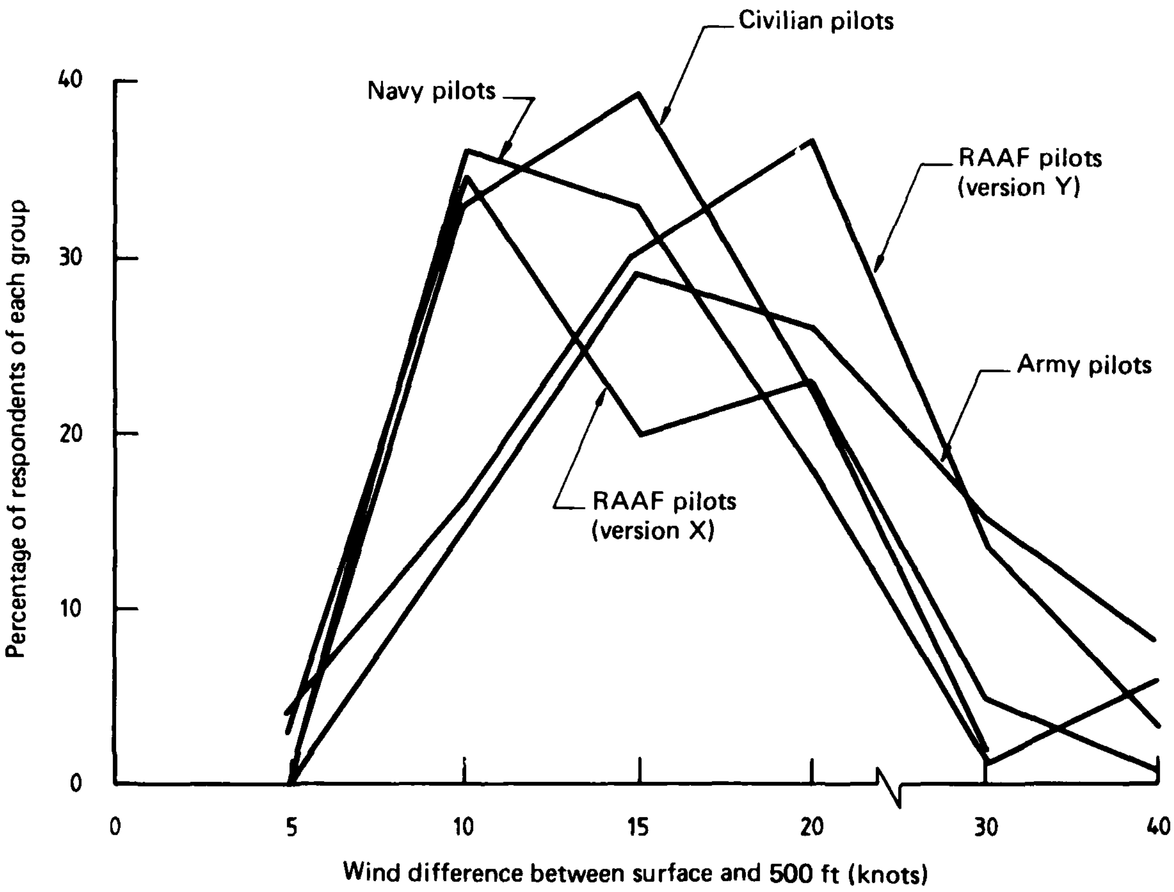

FIG. 4(b) SEVERITY CRITERIA FOR WIND ADVICE: PERCENTAGE OF RESPONDENT NOMINATIONS FOR EACH OPTION.

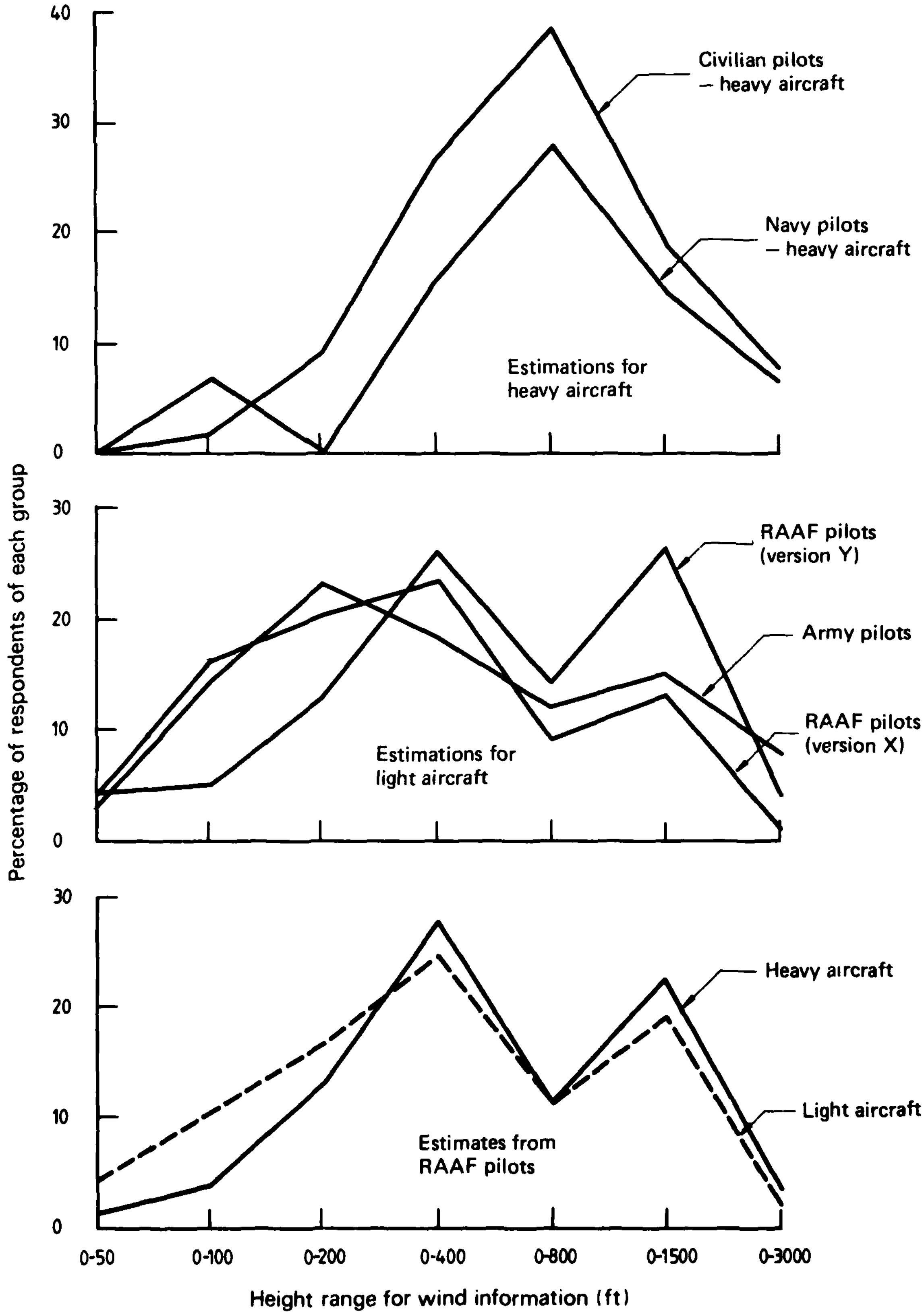

FIG. 5 HEIGHT RANGE FOR WIND STRUCTURE INFORMATION FOR HEAVY AND LIGHT AIRCRAFT : PERCENTAGE OF RESPONDENTS FROM EACH FUNCTIONAL GROUP FOR EACH OPTION.

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